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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2276

STATIC AND FATIGUE STRENGTHS OF HIGH-STRENGTH
ALUMINUM-ALLOY BOLTED JOINTS

By E. C. Hartmann, Marshall Holt, and I. D. Eaton

Aluminum Company of America

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DALLAS, TEXAS



Washington
February 1951

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SUMMARY

Static and fatigue tests were made on several types of joints in 75S-T6, 24S-T4, and 14S-T6 high-strength aluminum-alloy extruded bar.

In the static tensile tests, the 75S-T6 double-shear joint withstood the highest ultimate load, 115,250 pounds, and the 75S-T6 clamped-keyed joint the lowest, 55,500 pounds, a ratio of 2.08 to 1. All specimens had the same net-section area.

In order to evaluate the sensitivity of the materials to the effects of a notch consisting of two open holes, a monobloc specimen was tested under a mean load of 16,000 pounds. No consistent difference was found in fatigue life of the 75S-T6, 24S-T4, or 14S-T6 monobloc specimens; there was no significant difference between the apparent fatigue-strength reduction factors for 75S-T6, 24S-T4, or 14S-T6 monobloc specimens. Under a mean load of 16,000 pounds and for the portion of the fatigue curves established by these tests, the fatigue life of the 24S-T4 plain-scarf joints was greater than that of the 75S-T6 joints of the same dimensions. The 75S-T6 double-scarf joint had the highest fatigue strength of all the joints studied.

When the critical net area was held constant the other design details had a greater effect in prolonging fatigue life than did a change in materials within the group studied. Under a mean load of 16,000 pounds and a stress ratio of 0.5, the fatigue life of the double-scarf joint was over 800 times as great as the fatigue life of the nonuniform-step joint; the fatigue life of the 24S-T4 plain-scarf joint was 18 times the fatigue life of the 75S-T6 plain-scarf joint. A greater increase in fatigue life was obtained by a decrease of 25 percent in the mean load from 16,000 to 12,000 pounds on the 75S-T6 plain-scarf joint than was obtained by changing from 75S-T6 to 24S-T4 of the same dimensions, the mean load remaining at 16,000 pounds.

There was no evident correlation between the static and fatigue strengths of the joints studied when the static strengths were

compared with fatigue strengths based on: (a) Fatigue life at $16,000 \pm 5330$ pounds, (b) fatigue life at $16,000 \pm 10,670$ pounds, or (c) fatigue loading at 16,000 pounds mean load to failure at 80,000 cycles.

INTRODUCTION

As aluminum alloys with even higher static strengths have been developed and utilized for structures, fatigue characteristics have become increasingly important. A number of reports have been published presenting the results of investigations of the fatigue characteristics of high-strength aluminum alloys. For many years the Aluminum Research Laboratories of the Aluminum Company of America have contributed to such studies with reports on investigations of fatigue strengths of aluminum alloys and of structural components prepared from such alloys. Another such study, recently completed and reported herein, is an investigation to evaluate the effects of several design details on the static and fatigue strengths of bolted joints (simulating aircraft spar-cap splices) in high-strength aluminum alloys.

The investigation included: (a) Comparisons of several types of joint design, (b) comparisons of 75S-T6, 24S-T4, and 14S-T6 aluminum alloys, and (c) an evaluation of the sensitivity of the materials to the effects of a notch consisting of two open holes similar to those used in the joints.

The Aluminum Company of America has made this work available to the NACA for publication because of its general interest.

MATERIAL

Aluminum-alloy extruded bar $1\frac{1}{4}$ by 4 inches of 75S-T6, 24S-T4, and 14S-T6 was used for fabrication of the specimens tested in this investigation. The mechanical properties of the bar stock given in table I compare favorably with typical values published in reference 1. The materials satisfy the requirements of the applicable specifications given in reference 2.

Direct-stress, tension-compression, fatigue tests were made under the direction of Mr. F. M. Howell, Chief, Mechanical Testing Division, on round polished specimens taken from the 75S-T6, 24S-T4, and 14S-T6 alloy bars. The results of these tests, which were made using the ARL Direct-Tension and Compression Fatigue Testing Machines shown in

figure 5 of reference 3, are presented in figures 1(a), 1(b), and 1(c) and are summarized in table II. In general the fatigue strengths of the 75S-T6, 24S-T4, and 14S-T6 alloys used in this investigation compare favorably with and are slightly higher than typical fatigue strengths presented in table 3.112 of reference 2 and in table 6 of reference 4. The fatigue strengths presented herein exceed the reference results in the range of low number of cycles and, in the case of 75S-T6, in the range of higher positive stress ratios.

TEST SPECIMENS

The specimens used in this investigation were designed under the direction of Mr. R. L. Templin, Assistant Director of Research and Chief Engineer of Tests of Aluminum Research Laboratories. The details of the specimens are shown in figures 2(a) to 2(j). The 75S-T6 specimens were all designed for a nominal stress of 80,000 psi on a critical net section of 1.2 square inches to withstand a static ultimate load of 96,000 pounds. Aircraft-type fasteners were used throughout, the nuts being tightened with torques of 690, 175, and 70 inch-pounds for the 1/2-inch-, 3/8-inch-, and 1/4-inch-diameter fasteners, respectively.

The clamped-keyed joint (fig. 2(i)) has no bolt holes in the main plates and the monobloc specimens (fig. 2(a)) were tested with open holes, drilled and reamed to 0.500-inch diameter. With the exception of the bolted-keyed joints (fig. 2(d)) the holes in the remaining joints were reamed 0.001 to 0.002 inch under the measured bolt diameter; thus the joints were assembled with an interference of this amount. In the bolted-keyed joints the holes were reamed about 0.007 inch over the bolt diameter.

Previous to assembly all joints were given a chromic acid anodic treatment and a coat of zinc-chromate primer; in addition, the faying surfaces of one plain-scarf joint were treated with molybdenum-disulfide powdered lubricant (secured under the trade name Molykote). The monobloc specimens were tested without surface treatment. The first two bolted-keyed joints were assembled by driving the keys into place after the bolts had been tightened. This technique was found to cause scratches in the keyways and as a result the third bolted-keyed joint and the clamped-keyed joints (fig. 2(i)) were assembled by placing the keys in the keyways previous to bolting the plates together.

Only 75S-T6 alloy was used for all types of specimens. Alloys 24S-T4 and 14S-T6 were used, for comparison, in the monobloc specimens (fig. 2(a)) and plain-scarf joints (fig. 2(c)). The specimens of 24S-T4 and 14S-T6 were made identical in size to the 75S-T6 specimens without regard to differences in mechanical properties.

PROCEDURE

Static and fatigue tests were made on specimens of the types shown in figures 2(a) to 2(j). The static tests were made in an Amsler Universal Testing Machine¹ of the hydraulic type having a maximum capacity of 300,000 pounds. The test setup is shown in figure 3. Deformations were determined from dial-gage measurements over an 8-inch gage length on each edge of the specimen. Measurements were made after each of several increments of load, the loading being continued to failure of the specimen.

In the fatigue tests, the specimens were subjected to a cyclic loading superimposed on a steady load. In general, the load cycle was entirely within the tensile range; that is, the steady load was sufficiently high that, with the addition of the cyclic load, the total load was still tensile. For example, for a steady or mean load of 16,000 pounds and a cyclic or variable load of ± 5330 pounds the total load varied from a tension of 10,670 to a tension of 21,330 pounds. The ratio of minimum load to maximum load is designated stress ratio and in the above example is equal to 0.5. Several specimens were tested at a zero stress ratio, in which case the load cycle varied from zero to a maximum in tension. In addition some testing was done with negative stress ratios. For one series of these tests the stress ratio was -0.33 so that, when the mean load was 16,000 pounds, the variable load was $\pm 32,000$ pounds, and the total load varied from a compression of 16,000 to a tension of 48,000 pounds.

The majority of the fatigue tests were made in the Aluminum Research Laboratories Structural Fatigue Testing Machines described in reference 5 and shown in the foreground of figure 4. The test setup is shown in figure 5. The desired test conditions were obtained by (a) adjustment of the crank displacement to obtain the desired variable load and (b) adjustment of the turnbuckle at the crank end of the loading beam to obtain the desired mean load. The specimen was then subjected to the desired test conditions for a few cycles (ranging from 300 to 2100 cycles depending upon the expected fatigue life); it developed that these cycles never exceeded 10 percent and were usually considerably less than 1 percent of the total cycles to failure. The loading was checked after this preliminary run, the machine was readjusted to the desired test conditions if necessary, and the test was continued. Periodic checks were made to assure that the desired load conditions were maintained throughout the test. Further, the automatic cut-off switch, an integral part of the

¹Type 150 SZBDA Serial No. 5254. Periodic calibration of this machine indicated that the error in load reading is less than 1 percent throughout the load range used.

machine, was set so that a load change of less than 600 pounds would stop the machine. The tests were considered complete at the end of 25 million cycles of loading or when the specimen would no longer maintain the desired load conditions for a reasonable number of cycles, although, in many cases, the specimen had no visible fracture. In each such case the cyclic loading was continued until the fracture became apparent and in the case of the joints to complete fracture. Throughout this report the cycles of loading to the time when the specimen would no longer withstand the test conditions defines cycles to failure. The number of cycles of loading were determined by a counter which indicated each 100 cycles of machine operation.

Since the capacity of the fatigue machines is 50,000 pounds, one monobloc specimen each of 75S-T6 and 14S-T6 and one plain-scarf joint of 75S-T6 were fatigue tested in the machine used for the static tests at maximum loads greater than 90 percent of the static ultimate load for the particular type of specimen. These specimens were loaded by means of the same adapters as were used for the static tests and were subjected to a load cycle from zero to a maximum in tension by the operator of the machine. The zero stress ratio was chosen since such test conditions are more conveniently controlled in the static testing machine.

RESULTS

Static Test Results

The results of the static tests are presented in figures 6(a) and 6(b) and are summarized in tables III and IV. It is evident that the static strengths of the 75S-T6 and 14S-T6 monobloc specimens are about 10 percent high and the 24S-T4 monobloc specimen about 3 percent low when compared with the tensile strengths of the materials. The performance of the three alloys in this test is consistent with the findings of a previous investigation reported in reference 6.

The static load-deformation characteristics of the several types of joints are presented in the curves of figure 6(b). The static test results are summarized in order of decreasing ultimate load in table IV. Included in the table are the weights of the joints based on the $10\frac{5}{8}$ -inch length of specimen between centers of fulcra (see figs 2(b) to 2(j)). It is evident that the 75S-T6 plain scarf joint has the highest static strength-weight ratio when compared on this basis. The strongest and stiffest joint is seen to be the 75S-T6 double-shear joint (fig. 2(g)), which displays almost exactly the same strength as the monobloc specimen.

In addition to the ultimate load of each type of joint there are several significant results obtained through study of these static tests. The plain-scarf joints (fig. 2(c)) of 75S-T6, 24S-T4, and 14S-T6 can be compared directly from their load-deformation curves shown in figure 6(b). It is seen that, while the ultimate loads of the plain-scarf joints in the three materials are in the same order as those of the monobloc specimens, the ultimate loads for the 75S-T6 and 14S-T6 plain-scarf joints are about 7 percent less than in the case of the monobloc specimens. The uniform-step joint (fig. 2(h)) withstood slightly higher static load and appears to be slightly stiffer than the nonuniform-step joint (fig. 2(b)). The behavior of the bolted- and clamped-keyed joints (figs. 2(d) and 2(i), respectively) and of the serrated joint (fig. 2(e)) indicates that the bolts were insufficient to hold the parts together; at a static load of 32,000 pounds in all three joints the first visible separation of the faying surfaces was observed. This investigation was not concerned with determining the bolt area required to overcome this condition.

The static failure of the 75S-T6 monobloc specimen, which is almost identical to the failure observed in the 24S-T4 and 14S-T6 specimens, is shown in figure 7(a). The static failures of the 75S-T6 joints are illustrated in figure 7(b). The failures of the 14S-T6 and 24S-T4 plain-scarf joints are not included since they were almost identical to the failure obtained in 75S-T6 (specimen 2N). Both the bolted- and clamped-keyed joints failed as a result of insufficient clamping forces; the faying surfaces parted and rode over the keys, shearing the edges of the keyways and/or the keys, and finally in the bolted-keyed joint the bolts sheared. The serrated joint was observed to have appreciable elongation of the bolts and parting of the faying surfaces previous to the static failure. It was evident that the taper chosen for the double-scarf joint was of such proportions that a low static strength developed as a result of insufficient bearing area at a critical section of the joint. This joint failed in combined bearing and tension.

Fatigue Test Results

The results of the fatigue tests on the monobloc specimens are given in table V and in figures 8 and 9. There appears to be more scatter in the results from the 75S-T6 monobloc specimens than in the case of the 24S-T4 or 14S-T6 specimens. This may result from the fact that a larger number of 75S-T6 specimens were tested because of some failures outside the test section. No attempt was made to determine the width of the scatter bands for the 24S-T4 or 14S-T6 monobloc specimens. It is evident from figures 8 and 9 and the summary in tables VI and VII that there is little difference between the fatigue strengths of 75S-T6, 24S-T4,

and 14S-T6 monobloc specimens; certainly no one alloy has the advantage over another throughout the range of cycles considered in this investigation.

In figure 10 the results of tests on the monobloc specimens are compared with results from polished round specimens. The curves for a given number of cycles in these modified Goodman type diagrams represent the results, from table II, of the tests on polished specimens. The plotted points on the diagrams represent the results obtained from the monobloc specimens, from table VII. Radial lines from the origin of these diagrams are lines of constant stress ratio. Such lines have been drawn through the plotted points and extended to meet the curve for the same number of cycles on polished specimens. These diagrams are summarized in table VIII.

The apparent fatigue-strength reduction factors appearing in the table are the ratios of fatigue strength of the polished specimen to the fatigue strength of the monobloc specimen at like numbers of cycles and like stress ratios. There appears to be no consistent nor significant difference in the apparent fatigue-strength reduction factors for the 75S-T6, 24S-T4, or 14S-T6 monobloc specimens.

The results of the fatigue tests on the aluminum-alloy joints are given in table IX and figures 11 to 13. The results from the plain-scarf joints in 75S-T6, 24S-T4, and 14S-T6 aluminum alloys are shown in figure 11. Mean loads of 12,000 and 16,000 pounds were included for the 75S-T6 joints. From the summary in table X, it appears that with a mean load of 16,000 pounds and certain stress ratios the 24S-T4 joint has longer fatigue-life expectancy than the 75S-T6 joint, the difference in life being quite pronounced when the stress ratio equals 0.5 and being insignificant when the stress ratio equals -0.33. From figure 13 it appears that at less than 1000 cycles the fatigue strength of the 75S-T6 plain-scarf joint exceeds that of the 24S-T4 plain-scarf joint by virtue of its higher tensile strength. For fatigue lives greater than about 1000 cycles the variable load which can be superimposed on a mean load of 16,000 pounds is greater for the 24S-T4 joint than for the 75S-T6 joint. On the other hand, table X indicates that a 25-percent reduction in stress is considerably more effective in prolonging the fatigue life of a plain-scarf joint than is the change in alloy from 75S-T6 to 24S-T4. It is to be expected that the range of fatigue life in which one material has the advantage over the other is a function of the mean stress level. This investigation was not extensive enough to determine the mean stress level at which 75S-T6 has the advantage for all practical fatigue lives.

Included in table IX and in figure 11 is the result of the test on a plain-scarf joint which had been treated with Molykote on its faying

surfaces and it appears from this single comparison that this treatment had no effect on the fatigue life of this type of specimen, although the appearance of the faying surfaces after the test indicates that the Molykote did reduce the fretting on the faying surfaces.

The fatigue results of the various types of joints in 75S-T6 with a 16,000-pound mean load are plotted in figures 12 and 13. Included in figure 12 is a reference plot of the results from the 24S-T4 plain-scarf joints, and figure 13 includes the results from the 24S-T4 and 14S-T6 plain-scarf joints and a reference plot of the 75S-T6 monobloc curve. These results are summarized in table XI, where the joints are listed in the order of decreasing number of cycles to failures. Ratios of fatigue life are given, one based on the fatigue life of the 24S-T4 plain-scarf joint and the other on the life of the nonuniform-step joint in 75S-T6. It is seen that the ratio for the double-scarf joint, which represents the best fatigue design, as compared with that for the nonuniform-step joint, which represents the poorest fatigue design, is greater than 800 to 1 at a stress ratio of 0.5. Comparing the results from the ± 5330 -pound variable load (0.5 stress ratio) with those from the $\pm 10,670$ -pound variable load (0.2 stress ratio), it is evident that the improvements or losses in fatigue life as reflected in either fatigue-life ratio are less significant at the higher loading than at the lower loading. It is also indicated that assembling the bolted-keyed joints by clamping rather than by driving the keys results in an increase in fatigue life from 1,160,000 to 2,457,000 cycles at a load of 16,000 ± 5330 pounds. This is probably the result of avoiding sharp scratches in the keyways. The clamped-keyed joint does not appear to be so good as the bolted-keyed joint, probably because of a deficiency in the clamping force. It seems reasonable to believe, however, that a clamped-keyed joint with sufficient clamping force and without the complication of bolt holes would have a longer fatigue life than a similar bolted-keyed joint.

Figure 14 shows fatigue curves for zero stress ratio from figures 9 and 13 and also the results of cyclic loading tests which were made at relatively high loads in the static testing machine. These results confirm that the shape of these curves is similar to that of curves for several other specimen types currently being tested in this Laboratory. Included in this figure is a curve of the calculated maximum load which a polished specimen of the same cross-sectional area would support. This was derived as the stress from figure 1(a) times the nominal cross-sectional area of 1.2 square inches. Under the high-load cyclic test conditions there was noticeable plastic deformation in the monobloc specimens as indicated by visible flow lines on the faces of the specimens adjacent to the reamed holes.

All joints were disassembled following fatigue testing to determine whether or not additional failures existed. Further, each specimen was examined to determine the origin of failure; the monobloc specimens

which had not been completely fractured by the fatigue test were pulled apart in the static testing machine to permit inspection of their failures. As previously noted the cyclic loading of the joints was continued to complete fracture.

The failures in the test section of the monobloc specimens went through one or both reamed holes. In many cases the visible failure was limited to a small portion of the section because of the sensitivity of the automatic cut-off switch. Figure 15(a) illustrates a typical section through the failure of these specimens. The visible failure originated at the outside edge of the upper bolt hole in figure 15(a). Additional failures, at the inside edge of the upper bolt hole and at the outside edge of the lower bolt hole, were observed after the specimen was pulled apart. Over 50 percent of the monobloc specimens had additional failures which were not visible previous to fracture of the specimen. The majority of these invisible failures were similar to those shown; a few originated at the junction of the bolt holes with the specimen face.

Typical fatigue failures of the bolted joints are shown in figure 15(b). The principal failures in the nonuniform-step joints originated at the edge of the bolt holes. In specimen 1 the first visible failure, which was observed in the fillet of the end step in the intact portion of the joint, appeared after 21,500 cycles of loading. The more critical of the two failures, the one through the bolt holes, became visible after 22,600 cycles, and a failure in the fillet of the fractured portion of the joint was observed after 24,000 cycles of loading. Upon disassembly, an examination revealed an additional failure originating from one of the critical holes in the intact portion of this joint. The second nonuniform-step joint, specimen 1A, showed no evidence of fillet failures upon completion of the test at 32,400 cycles.

Without exception the principal fracture in the plain-scarf joints occurred through the first row of bolt holes. Inspections after disassembly of these joints indicated that the failures originated at bolt holes, and in several of the specimens cracks were found to have started in the critical bolt holes of the intact portion of the joint.

Two types of fatigue failures were obtained in the bolted-keyed joints. In the first two specimens of this type (3 and 3A) the keys were driven in after bolting the joint together and the fractures originated in a keyway. In specimen 3B, with the keys clamped in by bolting the joint together, the fracture originated in the bolt holes. An examination of specimen 3, after disassembly, showed no evidence of a failure starting in the keyway of the intact portion of the joint. Examination of specimens 3A and 3B by the Metallography Division of the Aluminum Research Laboratories revealed: (a) No failure near the critical bolt holes of specimen 3A, (b) fracture in specimen 3A definitely followed

scratches in the keyway although abrasion at the start of a fracture made it impossible to determine whether or not the fracture originated at any of several deep scratches in this region, and (c) no fracture in the critical keyways of specimen 3B.

The fatigue fracture in the serrated joint originated at the junction of the bolt holes and the bottom of a groove. In the single-shear joint the fracture originated at the junction of the fillet with the faying surface.

The critical fracture in the double-shear joint originated at the outside edge of each bolt hole in the center plate. An additional failure was found to have started in the fillet of the intact portion of the joint.

In the uniform-step joint the fracture originated at the edge of the bolt holes with no visible evidence of failure starting in the generous fillets. In the clamped-keyed joint the fracture originated at the bottom of a keyway.

The fatigue failure of the double-scarf joint originated at the edges of the holes in the tongue. There was no visible evidence of additional failures in the groove section of this joint.

SUMMARY OF RESULTS

From the foregoing data and discussion of static and fatigue tests on bolted joints in high-strength aluminum-alloy extruded bar, the following statements seem warranted:

1. The mechanical properties of the 75S-T6, 24S-T4, and 14S-T6 aluminum alloys used in this investigation are typical of the values obtained for these alloys.
2. The nominal average static strengths of the 75S-T6 and 14S-T6 monobloc specimens, which have a notch consisting of two 0.5-inch-diameter holes, are about 10 percent higher than the static strengths of the materials, while for the 24S-T4 specimens it is about 3 percent less than the strength of the material.
3. In the static tensile tests, the 75S-T6 double-shear joint (fig. 2(g)) withstood the highest ultimate load, 115,250 pounds, and the 75S-T6 clamped-keyed joint (fig. 2(i)) the lowest, 55,500 pounds, a ratio of 2.08 to 1. All specimens had the same net-section area.

4. The clamping forces for the keyed joints and the serrated joint were not sufficient to keep the faying surfaces in contact during the static tensile test, nor was the amount of clamping required to do so determined.

5. Direct-stress fatigue tests on polished round specimens of the 75S-T6, 24S-T4, and 14S-T6 alloys used in this investigation indicate that 75S-T6 has higher fatigue strengths than 24S-T4 or 14S-T6 aluminum alloy. These results for the three alloys compare favorably with published typical values.

6. Under a mean load of 16,000 pounds, there is no consistent difference in fatigue life of the 75S-T6, 24S-T4, or 14S-T6 monobloc specimens.

7. There is no significant difference between the apparent fatigue-strength reduction factors for 75S-T6, 24S-T4, or 14S-T6 monobloc specimens.

8. Under a mean load of 16,000 pounds and for the portion of the fatigue curves established by these tests the fatigue life of the 24S-T4 plain-scarf joints is greater than that of the 75S-T6 joints of the same dimensions. It follows that if the 24S-T4 joints had been designed for the same static load rather than being made to the same dimensions as the 75S-T6 joints their advantage in fatigue life would have been even greater, but on the other hand the weight of the joint would have been increased.

9. The 75S-T6 double-scarf joint has the highest fatigue strength of all the joints studied.

10. When the critical net area was held constant the other design details had a greater effect in prolonging fatigue life than did a change in materials within the group studied. Under a mean load of 16,000 pounds and a stress ratio of 0.5, the fatigue life of the double-scarf joint was over 800 times as great as the fatigue life of the nonuniform-step joint; the fatigue life of the 24S-T4 plain-scarf joint was 18 times the fatigue life of the 75S-T6 plain-scarf joint.

11. For a given value of stress ratio, a greater increase in fatigue life was obtained by a decrease of 25 percent in the mean load from 16,000 to 12,000 pounds on the 75S-T6 plain-scarf joint than was obtained by changing from 75S-T6 to 24S-T4 of the same dimensions, the mean load remaining at 16,000 pounds.

12. There is no evident correlation between the static and fatigue strengths of the joints studied when the static strengths are compared

with fatigue strengths which are based on: (a) Fatigue life at 16,000 $\pm$ 5330 pounds, (b) fatigue life at 16,000 $\pm$ 10,670 pounds, or (c) fatigue loading at 16,000 pounds mean load to failure at 80,000 cycles.

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TABLE I

MECHANICAL PROPERTIES OF MATERIALS USED IN FATIGUE TESTS
OF HIGH-STRENGTH ALUMINUM-ALLOY BOLTED JOINTS

[Standard 0.5-in. round specimens,¹ cut longitudinally
from $1\frac{1}{4}$ - by 4-in. extruded bar]

Alloy and temper	Material lot number	Tensile strength (psi)	Yield strength (psi) (2)	Elongation in 2 in. (percent)
75S-T6	119561-1	82,700	74,200	12.0
75S-T6	119561-2	85,600	76,900	12.0
75S-T6	119561-2	86,900	79,800	12.5
75S-T6	119561-4	87,500	81,000	12.5
75S-T6	119561-5	88,800	81,400	12.0
75S-T6	119561-6	90,200	83,000	11.5
75S-T6	Av.	86,950 ✓	79,400	12.1
14S-T6	119559-1	73,400	66,000	11.0
14S-T6	119559-3	75,600	69,000	9.0
14S-T6	119559-4	73,900	67,000	10.0
14S-T6	Av.	74,300	67,300	10.0
24S-T4	119560-1	81,000	62,400	14.5
24S-T4	119560-3	75,600	57,600	14.0
24S-T4	119560-4	77,200	58,600	14.0
24S-T4	Av.	77,900 ✓	59,500	14.2

¹Standard round test specimen. See fig. 3 of reference 7.

²Stress at offset of 0.2 percent. Templin Autographic Extensometer (500X).

TABLE II
SUMMARY OF RESULTS OF DIRECT-STRESS FATIGUE TESTS ON
POLISHED ROUND SPECIMENS OF MATERIAL USED IN TESTS
OF HIGH-STRENGTH ALUMINUM-ALLOY BOLTED JOINTS

Stress ratio (1)	Maximum stress (psi) to failure at -			
	10^4 cycles	10^5 cycles	10^6 cycles	10^7 cycles
75S-T6				
-0.33	74,500	50,000	41,500	36,500
0	83,000	59,000	48,500	42,500
.20	88,000	66,000	53,500	47,500
.50	89,300	81,000	64,000	57,500
24S-T4				
-0.33	64,000	48,000	37,000	30,000
0	70,000	55,000	43,500	36,500
.20	74,000	59,000	47,500	41,500
.50	81,000	70,000	57,000	52,000
14S-T6				
-0.33	66,000	49,000	39,500	34,500
0	71,000	55,000	46,000	41,500
.20	74,000	60,000	51,000	47,500
.50	75,000	68,500	61,500	59,500

¹Stress ratio equals minimum stress divided by maximum stress.

TABLE III

SUMMARY OF RESULTS OF STATIC TESTS ON HIGH-STRENGTH

ALUMINUM-ALLOY MONOBLOC SPECIMENS

Specimen	Alloy and temper	Load (lb)	Stress (psi) (1)	Location of failure	Tensile strength of material from table I (psi)
10-7	75S-T6	114,800	96,700	Through holes	86,950
10-17	14S-T6	98,200	81,900	Through holes	74,300
10-18	24S-T4	90,800	75,800	Through holes	77,900

¹Nominal stress, based on actual net area.

TABLE IV

SUMMARY OF RESULTS OF STATIC TESTS ON HIGH-STRENGTH ALUMINUM-ALLOY BOLTED JOINTS

Specimen	Description	Alloy and temper	Wt. of joint (lb) (1)	Ultimate load (lb)	Load per lb of wt. (lb) (1b)	Average deformation (in.) (2)	Location of failure
6A	Double-shear	75S-T6	4.25	115,250	27,100	0.0050	First row of bolts; center member
7A	Uniform-step	75S-T6	3.09	107,800	34,900	.0067	First row of bolts
2N	Plain-scarf	75S-T6	3.06	107,250	35,000	.0073	Second row of bolts
1B	Nonuniform-step	75S-T6	4.34	100,000	23,000	.0098	First row of bolts
2Q	Plain-scarf	14S-T6	3.09	91,500	29,600	.0058	Second row of bolts
2P	Plain-scarf	24S-T4	3.06	91,200	29,800	.0065	Second row of bolts
3C	Bolted-keyed	75S-T6	2.87	84,000	29,200	.0070	Bolt failure in tension and shear
9A	Double-scarf	75S-T6	3.79	76,600	20,200	.0065	Combined bearing and tension
5A	Single-shear	75S-T6	4.97	75,900	15,300	.0110	First row of bolts
4A	Serrated	75S-T6	2.81	69,000	24,500	.0080	First row of bolts
8A	Clamped-keyed	75S-T6	5.28	55,500	10,500	.0085	Slipped over and sheared pins

¹Weight based on length of $10\frac{5}{8}$ in. for each joint, distance between fulcra.

²Deformation measured under load of 16,000 lb over length of 8 in. for each joint.

TABLE V

RESULTS OF FATIGUE TESTS ON HIGH-STRENGTH ALUMINUM-ALLOY MONOBLOC SPECIMENS

Specimen	Alloy and temper	Actual load cycle (lb)				Computed maximum stress (psi)	Number of cycles to failure	Location of failure
		Minimum	Maximum	Mean	Variable			
10-26	75S-T6	0	^a 105,000	52,500	52,500	87,500	370	Through holes
10-3	75S-T6	-8000	40,000	16,000	24,000	33,300	36,600	From hole toward center
10-2	75S-T6	0	32,000	16,000	16,000	27,200	56,700	From hole toward center
10-24	75S-T6	0	32,000	16,000	16,000	26,600	298,100	Outside test section
10-21	75S-T6	5330	26,670	16,000	10,670	22,300	510,800	Between holes
10-4	75S-T6	5330	26,670	16,000	10,670	22,150	7,078,800	Outside test section
10-23	75S-T6	0	40,000	20,000	20,000	33,400	31,700	From hole to edge
10-22	75S-T6	6670	33,330	20,000	13,330	27,800	535,200	From hole to edge
10-19	75S-T6	6670	33,330	20,000	13,330	27,800	1,404,900	Outside test section
10-8	24S-T4	-8000	40,000	16,000	24,000	33,250	50,200	From hole toward edge
10-11	24S-T4	0	32,000	16,000	16,000	26,650	175,400	From hole to edge
10-10	24S-T4	5330	26,670	16,000	10,670	22,200	750,300	From hole to edge
10-9	24S-T4	8000	24,000	16,000	8,000	19,600	8,791,700	Between holes
^b 10-16	14S-T6	0	^a 92,500	46,250	46,250	77,000	354	Through holes
10-14	14S-T6	-8000	40,000	16,000	24,000	33,400	16,200	From hole toward edge
10-12	14S-T6	0	32,000	16,000	16,000	26,650	115,700	From hole to edge
10-15	14S-T6	5330	26,670	16,000	10,670	22,200	17,243,500	Outside test section
10-16	14S-T6	8000	24,000	16,000	8,000	19,950	29,095,100	No failure; removed

^aTested in Static Testing Machine.^bRetest after indicated previous test history; same specimen number.

TABLE VI

SUMMARY OF FATIGUE TEST RESULTS ON MONOBLOC SPECIMENS

Stress ratio (a)	Mean load (lb)	Variable load (lb)	Number of cycles to failure		
			75S-T6	24S-T4	14S-T6
0	20,000	±20,000	^b 32,000(0.2)		
.2	20,000	±13,370	900,000(0.1)		
-.33	16,000	±32,000	^c 19,000	^c 26,000(1.4)	^c 7,000(0.4)
0	16,000	±16,000	140,000	175,000(1.2)	115,000(0.8)
.2	16,000	±10,670	7,000,000	760,000(0.1)	>17,000,000(>2.4)

^aStress ratio equals minimum load divided by maximum load.

^bNumber in parentheses is ratio of fatigue life to that of 75S-T6 at 16,000-lb mean load and same stress ratio.

^cFrom extrapolated curve.

TABLE VII

SUMMARY OF RESULTS OF FATIGUE TESTS ON MONOBLOC SPECIMENS

Cycles to failure	Load (lb)		Nominal stress (psi) (a)		Stress ratio (b)
	Minimum	Maximum	Minimum	Maximum	
75S-T6					
10 ⁴	c-26,000	c58,000	-21,650	48,400	-0.45
10 ⁵	-1,500	33,500	-1,250	28,000	-.04
10 ⁶	4,000	28,000	3,340	23,400	.14
10 ⁷	5,200	26,800	4,330	22,300	.19
10 ⁴	c-6,800	c46,800	-5,670	39,000	-.15
10 ⁵	4,200	35,800	3,500	30,000	.12
10 ⁶	6,800	33,200	5,670	27,500	.21
24S-T4					
10 ⁴	c-31,000	c63,000	-25,800	52,500	-0.49
10 ⁵	-3,200	35,200	-2,670	29,400	-.09
10 ⁶	6,000	26,000	5,000	21,600	.23
10 ⁷	8,200	24,000	6,850	20,000	.34
14S-T6					
10 ⁴	c-12,000	c44,000	-10,000	36,700	-0.27
10 ⁵	-200	32,000	-170	26,700	-.01
10 ⁶	3,500	28,500	2,920	23,800	.12
10 ⁷	5,000	27,000	4,170	22,500	.18

^aBased on nominal net-section area of 1.2 in.².^bStress ratio equals minimum load divided by maximum load.^cFrom extrapolated curves.

TABLE VIII
SUMMARY OF RESULTS OF FATIGUE TESTS ON POLISHED
ROUND SPECIMENS AND MONOBLOC SPECIMENS

Cycles to failure	Stress ratio (a)	Maximum stress (psi)		Apparent fatigue-strength reduction factor (b)
		Polished specimen	Monobloc specimen	
75S-T6				
10 ⁴	-0.45	^c 71,800	48,400	1.5
10 ⁵	-.04	57,500	28,000	2.1
10 ⁶	.14	51,800	23,400	2.2
10 ⁷	.19	47,000	22,300	2.1
10 ⁴	-.15	79,200	39,000	2.0
10 ⁵	.12	62,700	30,000	2.1
10 ⁶	.21	53,700	27,500	2.0
24S-T4				
10 ⁴	-0.49	^c 61,700	52,500	1.2
10 ⁵	-.09	52,500	29,400	1.8
10 ⁶	.23	48,500	21,600	2.2
10 ⁷	.34	45,700	20,000	2.3
14S-T6				
10 ⁴	-0.27	67,000	36,700	1.8
10 ⁵	-.01	55,000	26,700	2.1
10 ⁶	.12	49,000	23,800	2.1
10 ⁷	.18	46,700	22,500	2.1

^aStress ratio equals minimum stress divided by maximum stress.

^bApparent fatigue-strength reduction factor; ratio of fatigue strength of polished specimen to fatigue strength of monobloc specimen at like number of cycles and like stress ratio.

^cFrom extrapolated curve.

TABLE IX

RESULTS OF FATIGUE TESTS ON HIGH-STRENGTH ALUMINUM-ALLOY BOLTED JOINTS

Specimen	Alloy and temper	Actual load cycle (lb)			Number of cycles to failure	Location of failure
		Minimum to maximum	Mean	Variable		
Nonuniform-step joints						
1 1A	75S-T6	5,310 to 26,890	16,100	10,790	22,600	Through first row of bolt holes
	75S-T6	10,580 to 21,220	15,900	5,320	31,300	Through first row of bolt holes
Plain-scarf joints						
2E ^a	75S-T6	0 to 100,000	50,000	50,000	253	Through first row of bolt holes
2J	75S-T6	-16,000 to 47,950	15,950	32,000	3,700	Through first row of bolt holes
2I	75S-T6	50 to 31,950	16,000	15,950	21,700	Through first row of bolt holes
2	75S-T6	5,260 to 26,540	15,900	10,640	70,600	Through first row of bolt holes
2F ^b	75S-T6	5,300 to 26,700	16,000	10,700	70,700	Through first row of bolt holes
2A	75S-T6	7,750 to 24,030	15,890	8,140	84,400	Through first row of bolt holes
2D	75S-T6	10,670 to 21,370	16,020	5,350	210,800	Through first row of bolt holes
2E	75S-T6	13,350 to 18,710	16,030	2,680	27,510,300	No failure; removed
2K	75S-T6	-12,000 to 36,000	12,000	24,000	13,500	Through first row of bolt holes
2H	75S-T6	4,000 to 20,000	12,000	8,000	212,700	Through first row of bolt holes
2G	75S-T6	8,005 to 15,965	11,985	3,980	26,039,600	No failure; removed
2M	24S-T4	20 to 31,960	15,990	15,970	45,300	Through first row of bolt holes
2L	24S-T4	5,330 to 26,670	16,000	10,670	197,000	Through first row of bolt holes
2C	24S-T4	10,650 to 21,350	16,000	5,350	3,897,000	Through first row of bolt holes
2B	14S-T6	10,680 to 21,320	16,000	5,320	364,000	Through first row of bolt holes
Bolted-keyed joints						
3 ^c	75S-T6	5,320 to 26,840	16,080	10,760	78,200	Through first keyway
3A ^c	75S-T6	10,630 to 21,370	16,000	5,370	1,160,100	Through first keyway
3B	75S-T6	10,640 to 21,320	15,980	5,340	2,457,100	Through first row of bolt holes
Serrated joint						
4	75S-T6	10,670 to 21,330	16,000	5,330	77,900	Through first row of bolt holes
Single-shear joint						
5	75S-T6	10,670 to 21,310	15,990	5,320	42,000	In fillet
Double-shear joint						
6	75S-T6	10,630 to 21,290	15,960	5,330	3,427,000	In tongue through first row of bolt holes
Uniform-step joint						
7	75S-T6	10,700 to 21,340	16,020	5,320	476,800	Through first row of bolt holes
Clamped-keyed joint						
8	75S-T6	10,660 to 21,300	15,980	5,320	166,400	Through first keyway
Double-scarf joint						
9B	75S-T6	0 to 32,000	16,000	16,000	86,500	First row of bolt holes; tongue
a ⁹	75S-T6	5,330 to 26,670	16,000	10,670	418,300	Failed outside test section ^d
9	75S-T6	10,670 to 21,330	16,000	5,330	26,194,600	No failure; removed

^aRetest after indicated previous test history; same specimen number.^bFaying surface covered with Molykote.^cKeys driven in after assembly.^dNo visible failure in test section.

TABLE X

SUMMARY OF FATIGUE TEST RESULTS ON PLAIN-SCARF JOINTS

Stress ratio (a)	Mean load (lb)	Variable load (lb)	Number of cycles to failure		
			75S-T6	24S-T4	14S-T6
-0.33	16,000	±32,000	3,700	^b 5,100 ^c (1.4)	-----
0	16,000	±16,000	21,700	45,300(2.1)	-----
.2	16,000	±10,670	55,000	197,000(3.6)	-----
.5	16,000	±5,330	210,800	3,897,100(18.5)	364,000(1.7)
-0.33	12,000	±24,000	13,500(3.6)	-----	-----
0	12,000	±12,000	73,500(3.4)	-----	-----
.2	12,000	±8,000	212,700(3.9)	-----	-----
.5	12,000	±4,000	^d >26,039,000(>100)	-----	-----

^aStress ratio equals minimum load divided by maximum load.

^bFrom extrapolated curve.

^cNumber in parentheses is ratio of fatigue life to that of 75S-T6 specimens at 16,000-lb mean load and same stress ratio.

^dNo failure; specimen removed.

TABLE XI
SUMMARY OF FATIGUE TEST RESULTS ON HIGH-STRENGTH
ALUMINUM-ALLOY BOLTED JOINTS

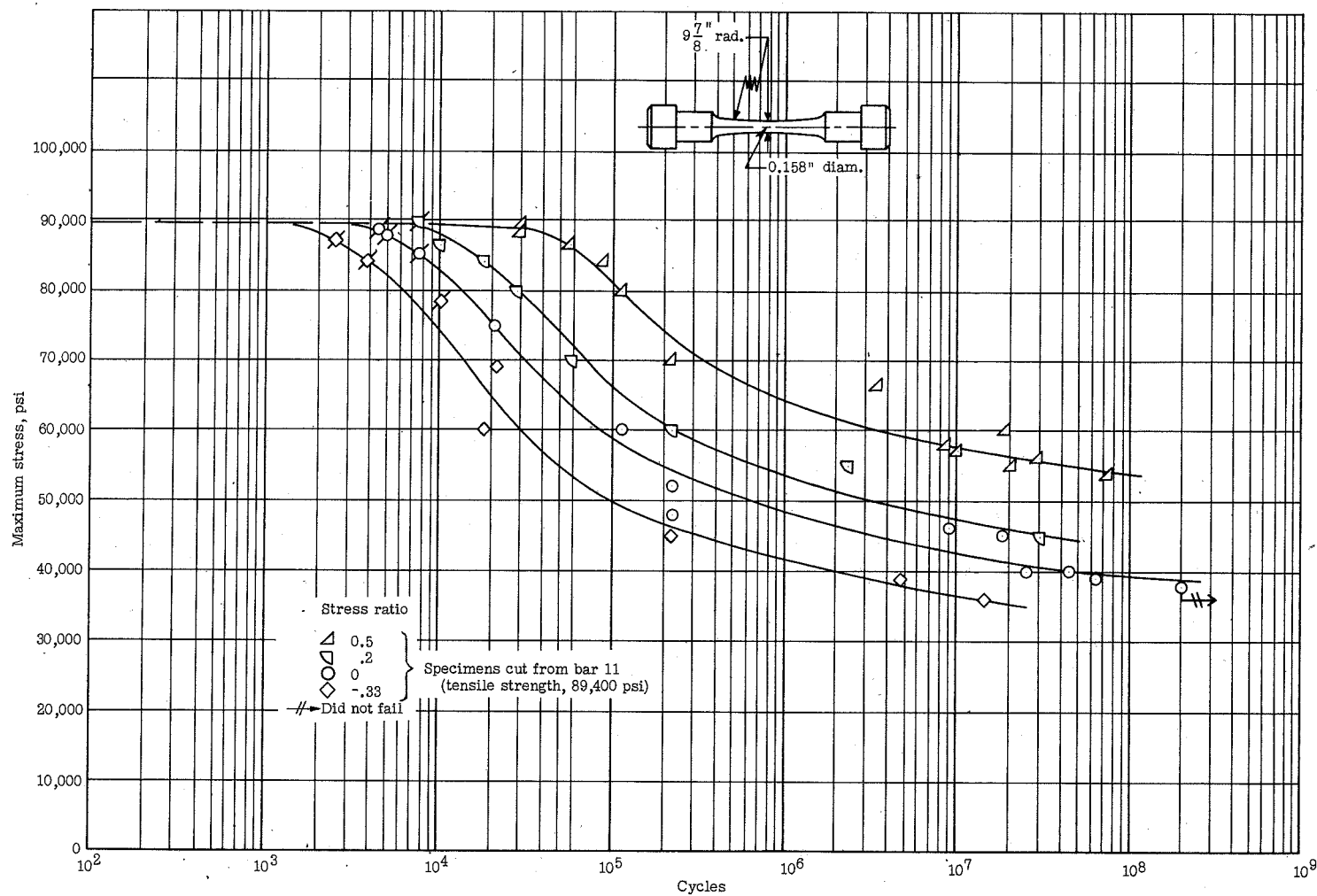
Specimen type	Alloy and temper	Number of cycles to failure	Fatigue life-ratio (1)	Fatigue life-ratio (2)
Fatigue life at 16,000-lb mean load; $\pm 5,330$ -lb variable load (Stress ratio, 0.5)				
Double-scarf	75S-T6	$>26,194,600$	>6.72	>830
Plain-scarf	24S-T4	$3,897,000$	1.00	120
Double-shear	75S-T6	$3,427,000$	.88	110
Bolted-keyed ³	75S-T6	$2,457,100$	.63	78
Bolted-keyed ⁴	75S-T6	$1,160,100$	.30	37
Uniform-step	75S-T6	$476,800$	.12	15
Plain-scarf	14S-T6	$364,000$	.09	12
Plain-scarf	75S-T6	$210,800$	.05	6.7
Clamped-keyed	75S-T6	$166,400$	.04	5.3
Serrated	75S-T6	$77,900$	.020	2.5
Single-shear	75S-T6	$42,000$	.011	1.3
Nonuniform-step	75S-T6	$31,300$	.008	1.0
Fatigue life at 16,000-lb mean load; $\pm 10,670$ -lb variable load (Stress ratio, 0.2)				
Double-scarf	75S-T6	$>418,000$	>2.12	>18.5
Plain-scarf	24S-T4	$197,000$	1.00	8.7
Bolted-keyed ⁴	75S-T6	$78,200$	.40	3.5
Plain-scarf	75S-T6	$55,000$	.28	2.4
Nonuniform-step	75S-T6	$22,600$	.11	1.0

¹Fatigue-life ratio equals cycles to failure (any joint) divided by cycles to failure for 24S-T4 plain-scarf joint.

²Fatigue-life ratio equals cycles to failure (any joint) divided by cycles to failure for 75S-T6 nonuniform-step joint.

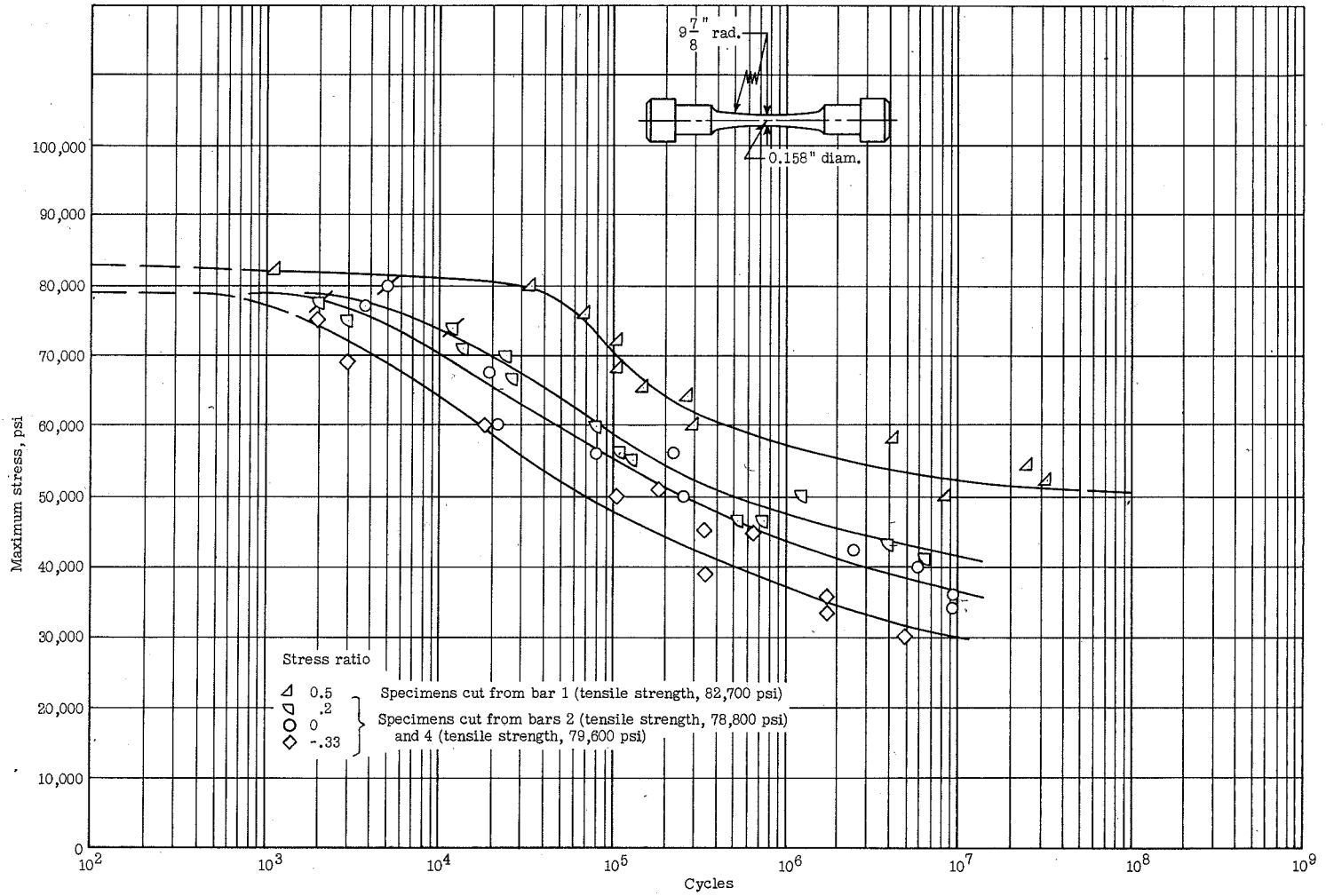
³Keys clamped in.

⁴Keys driven in.



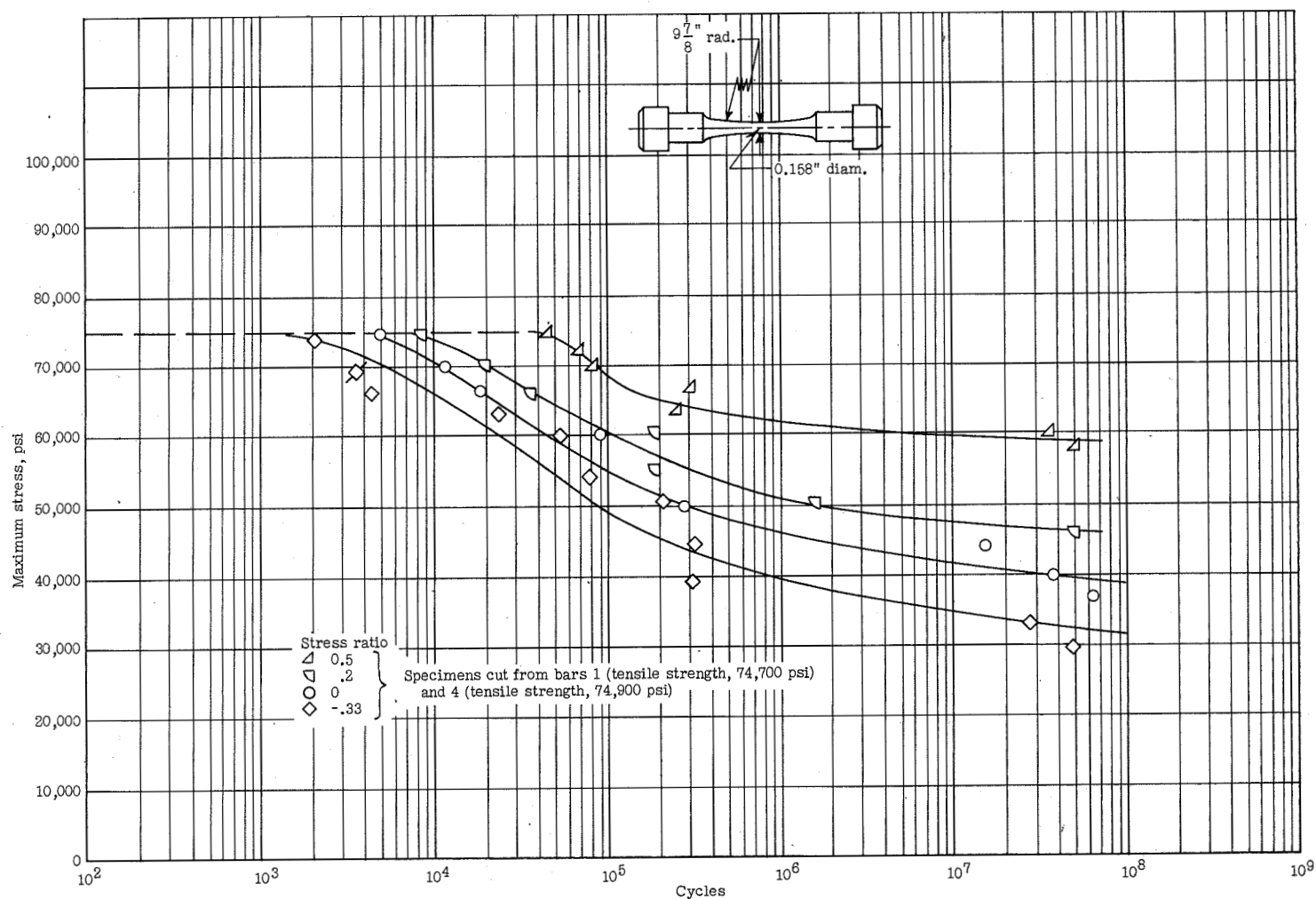
(a) 75S-T6 extruded bar.

Figure 1.- Direct-stress, tension-compression, fatigue curves. Diagonal line indicates test run by hand.



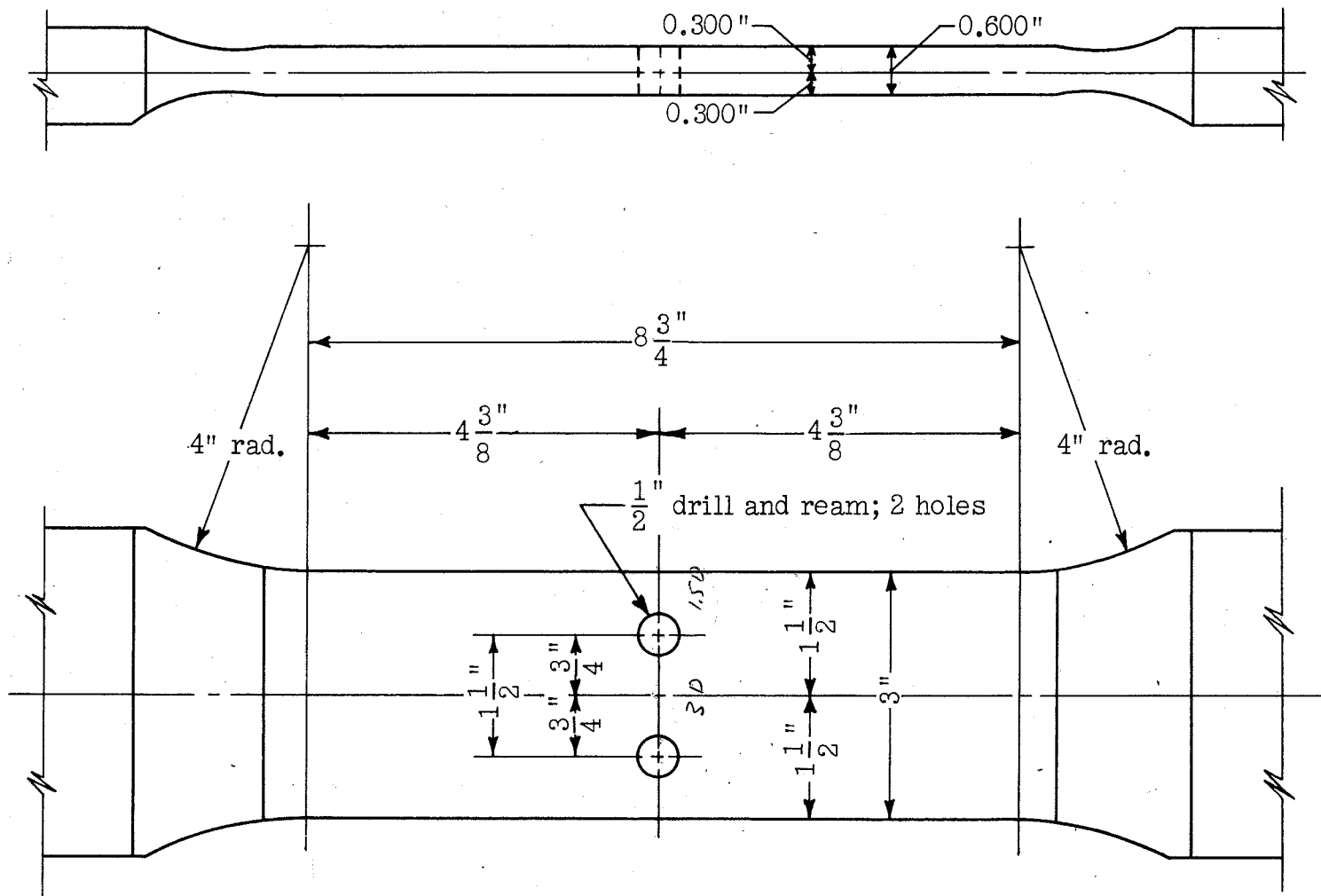
(b) 24S-T4 extruded bar.

Figure 1.- Continued.



(c) 14S-T6 extruded bar.

Figure 1.- Concluded.

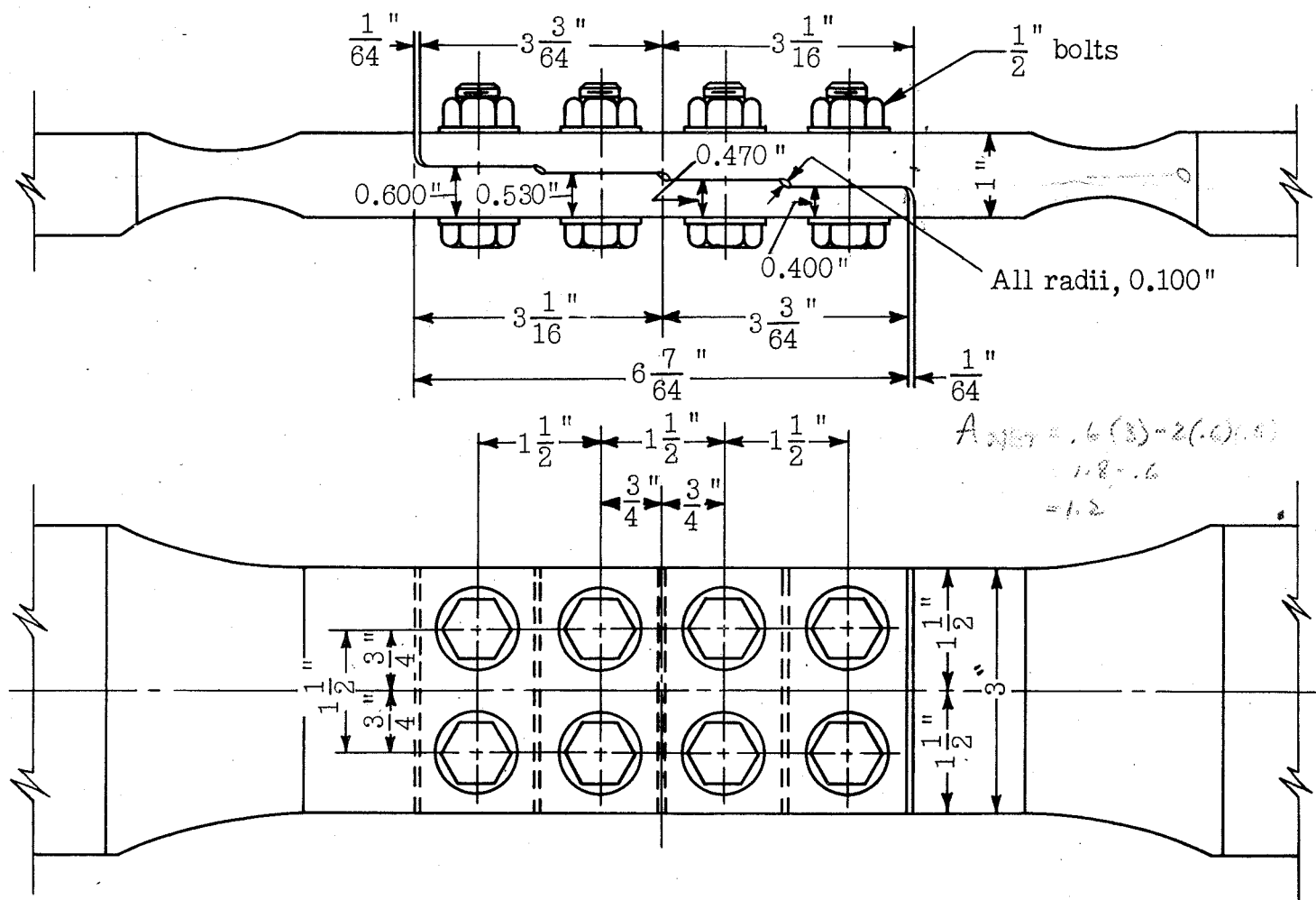


8'1

(a) Monobloc specimen.

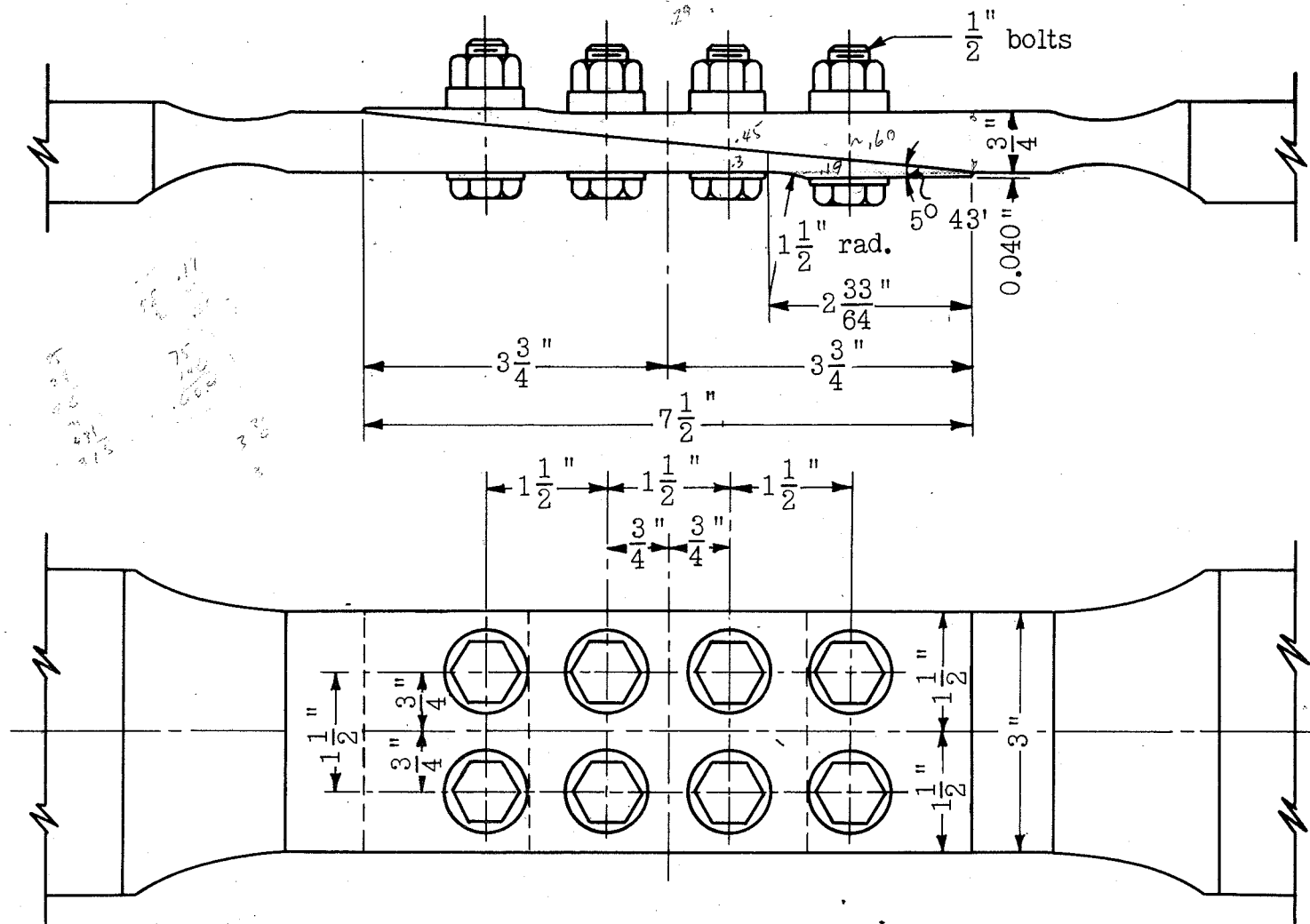
2'1

Figure 2.- Details of specimens tested.



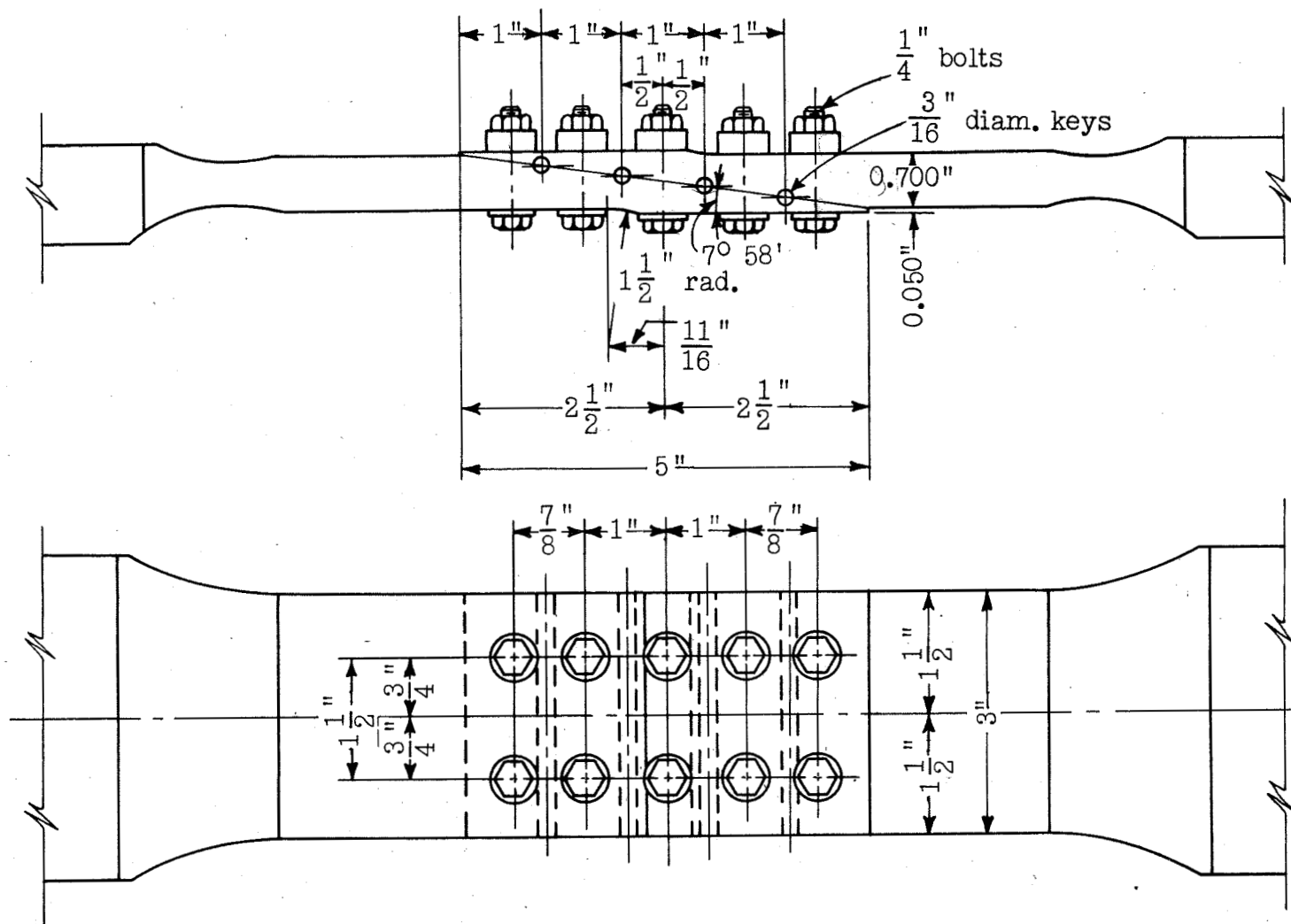
(b) Nonuniform-step joint specimen.

Figure 2.- Continued.



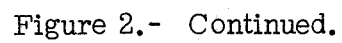
(c) Plain-scarf joint specimen.

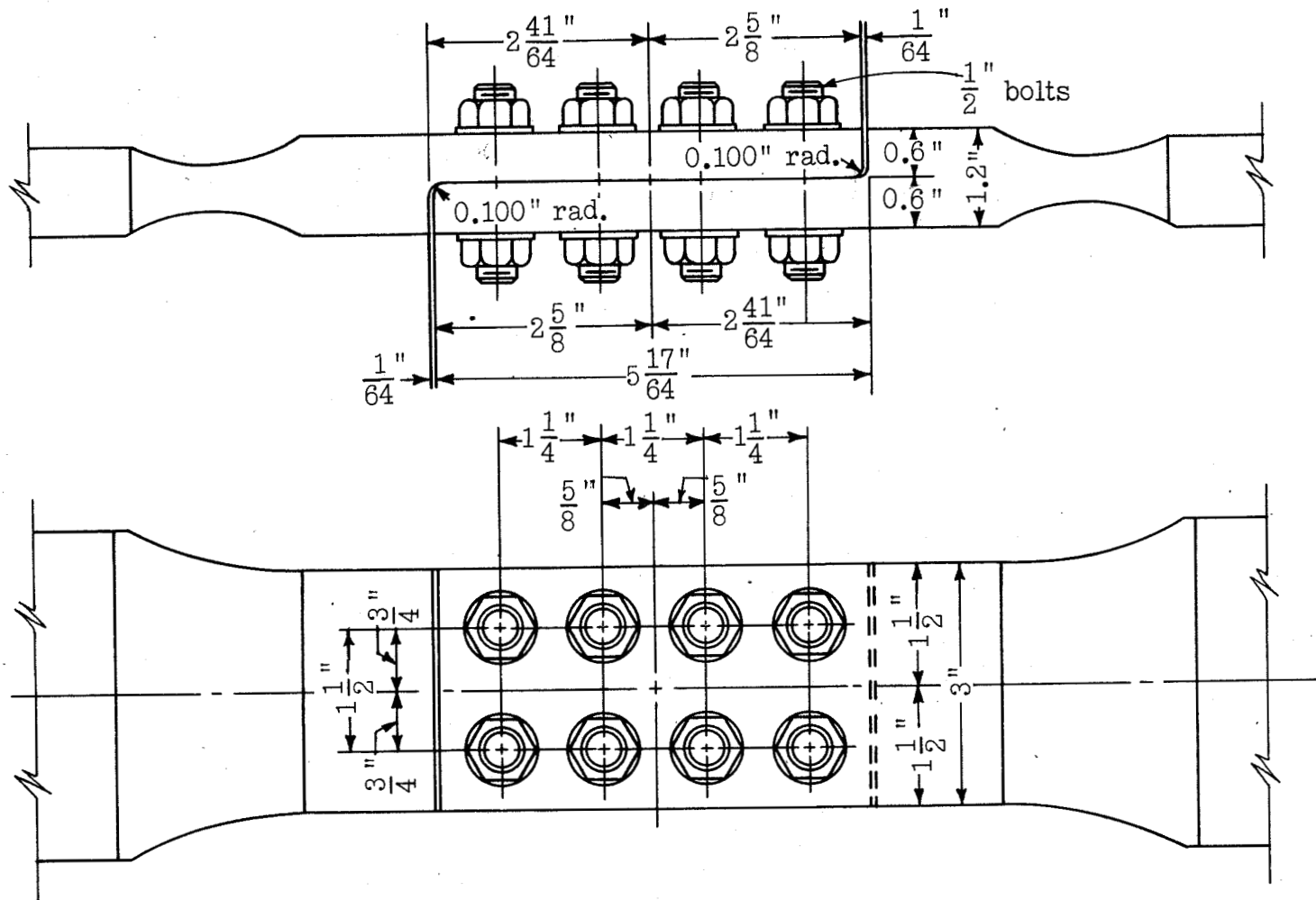
Figure 2.- Continued.



(d) Bolted-keyed joint specimen.

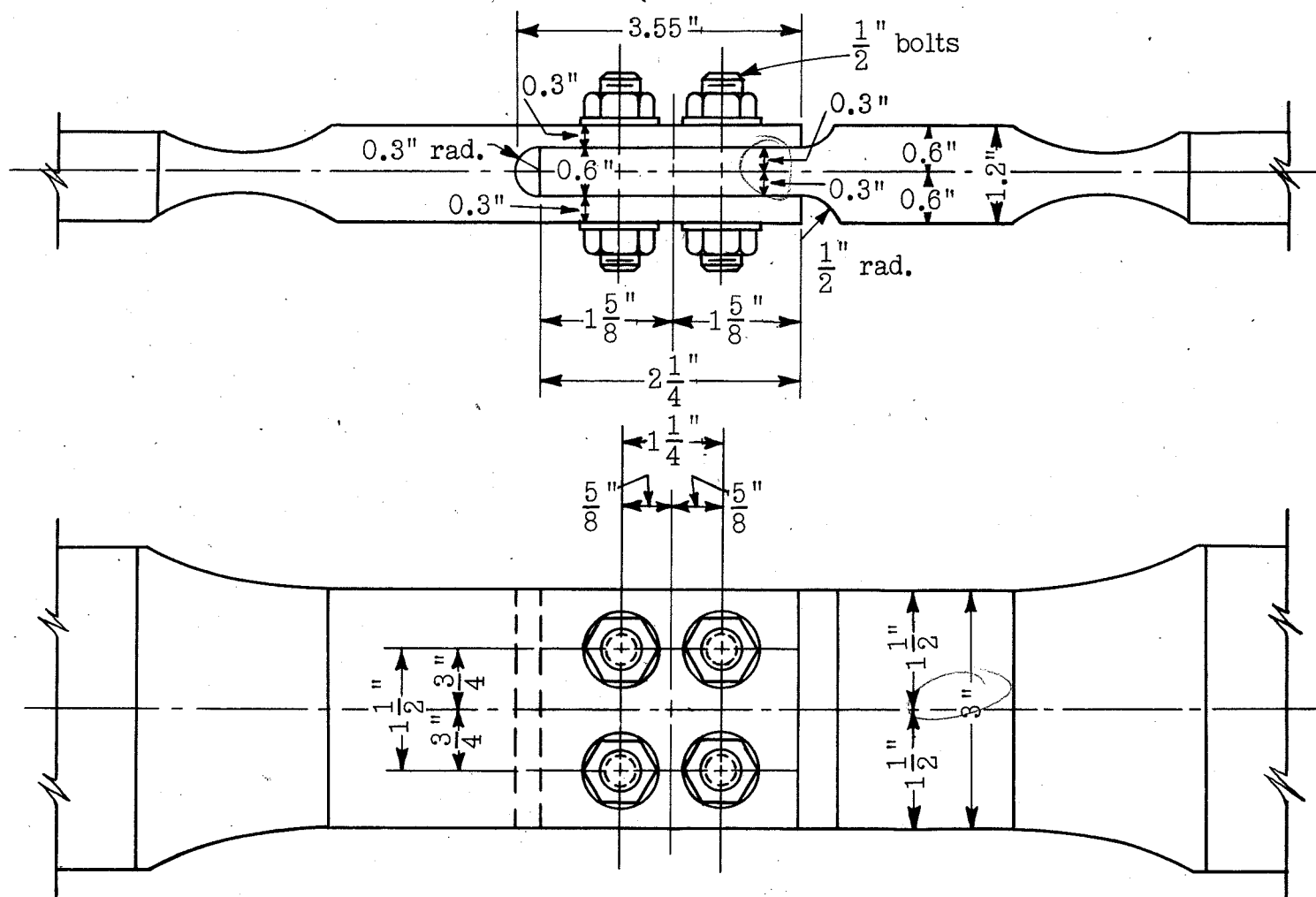
Figure 2.- Continued.





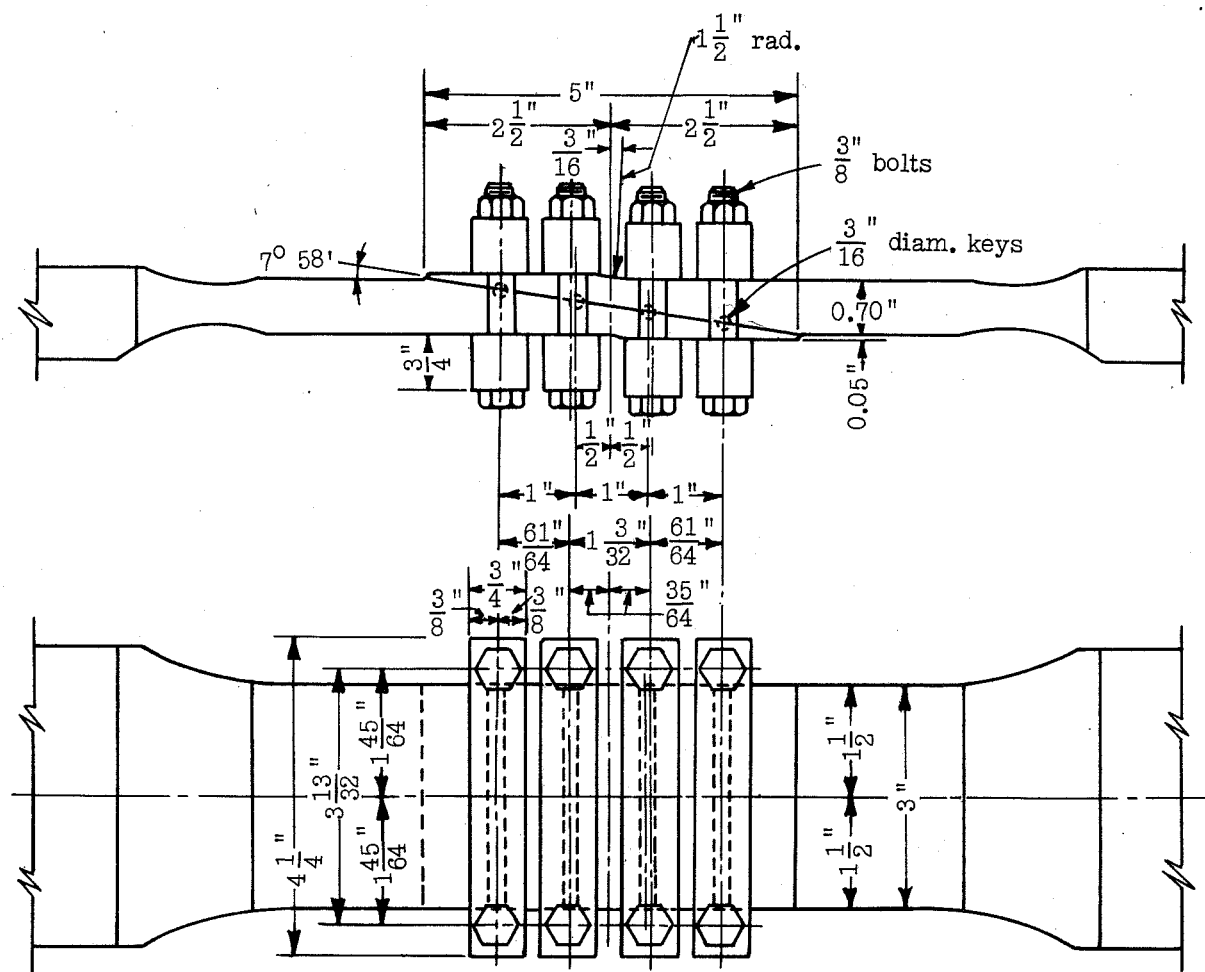
(f) Single-shear joint specimen.

Figure 2.- Continued.



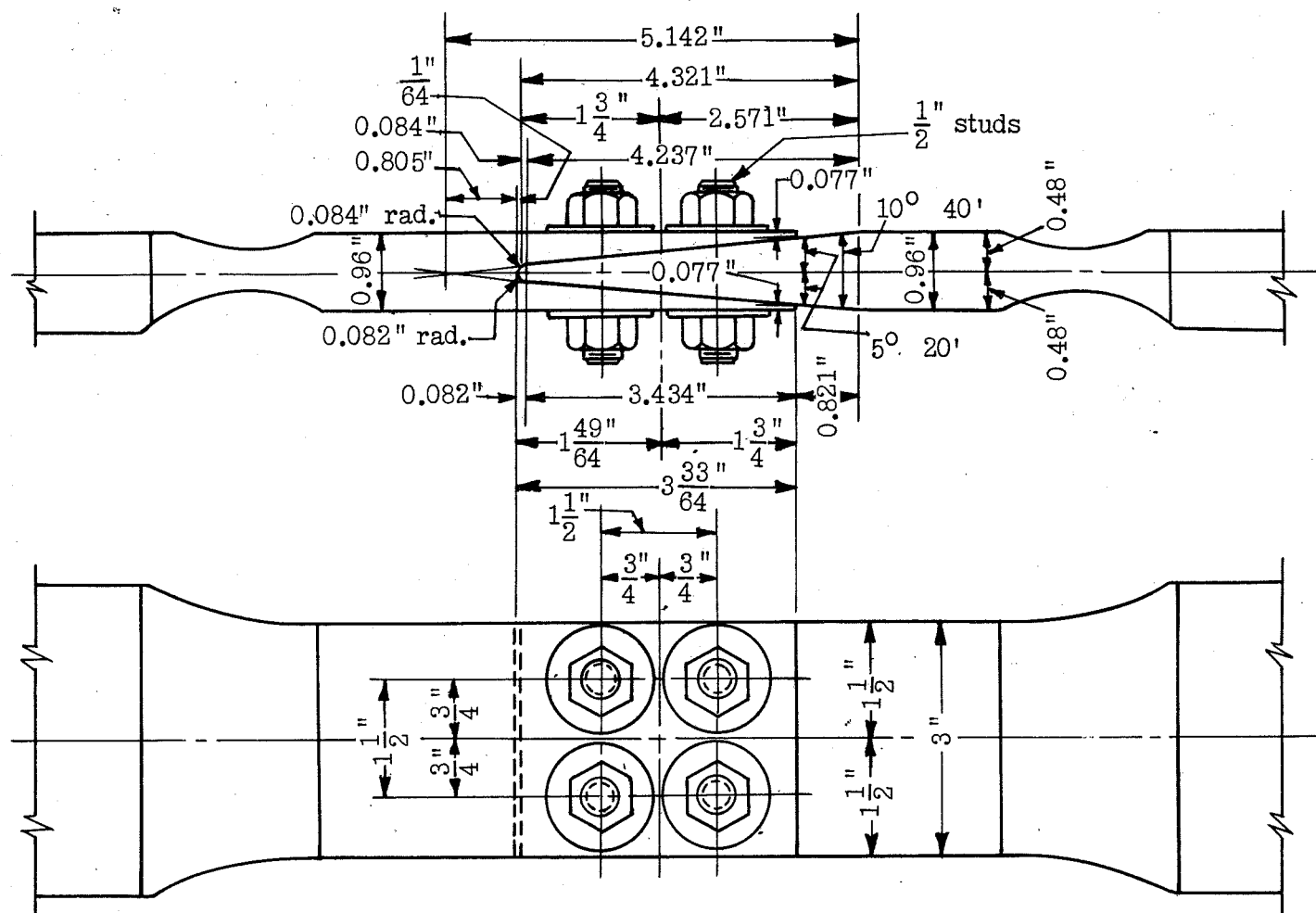
(g) Double-shear joint specimen.

Figure 2.- Continued.



(i) Clamped-keyed joint specimen.

Figure 2.- Continued.



(j) Double-scarf joint specimen.

Figure 2.- Concluded.

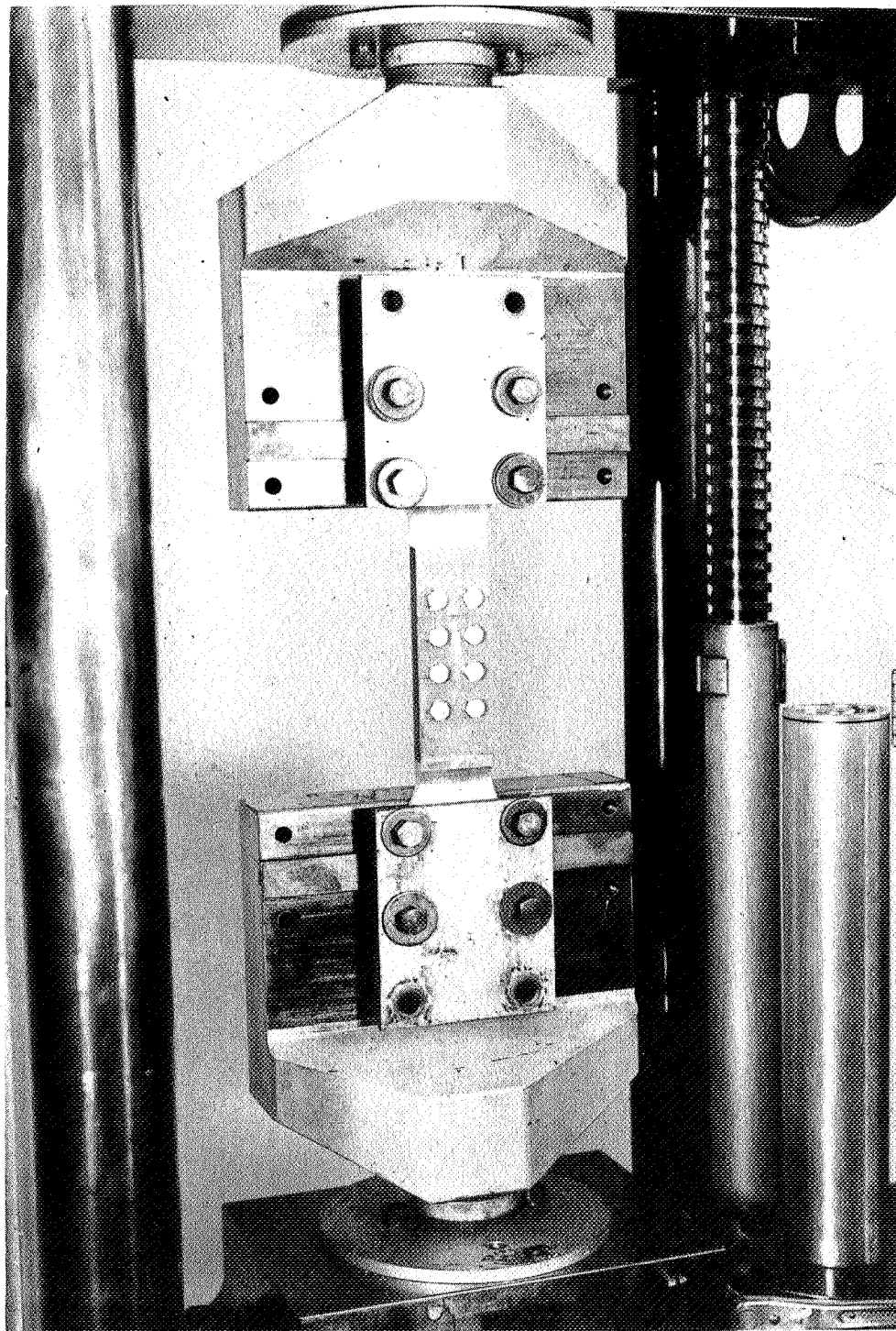


Figure 3.- Static test setup for tests on bolted joints of high-strength aluminum alloys.

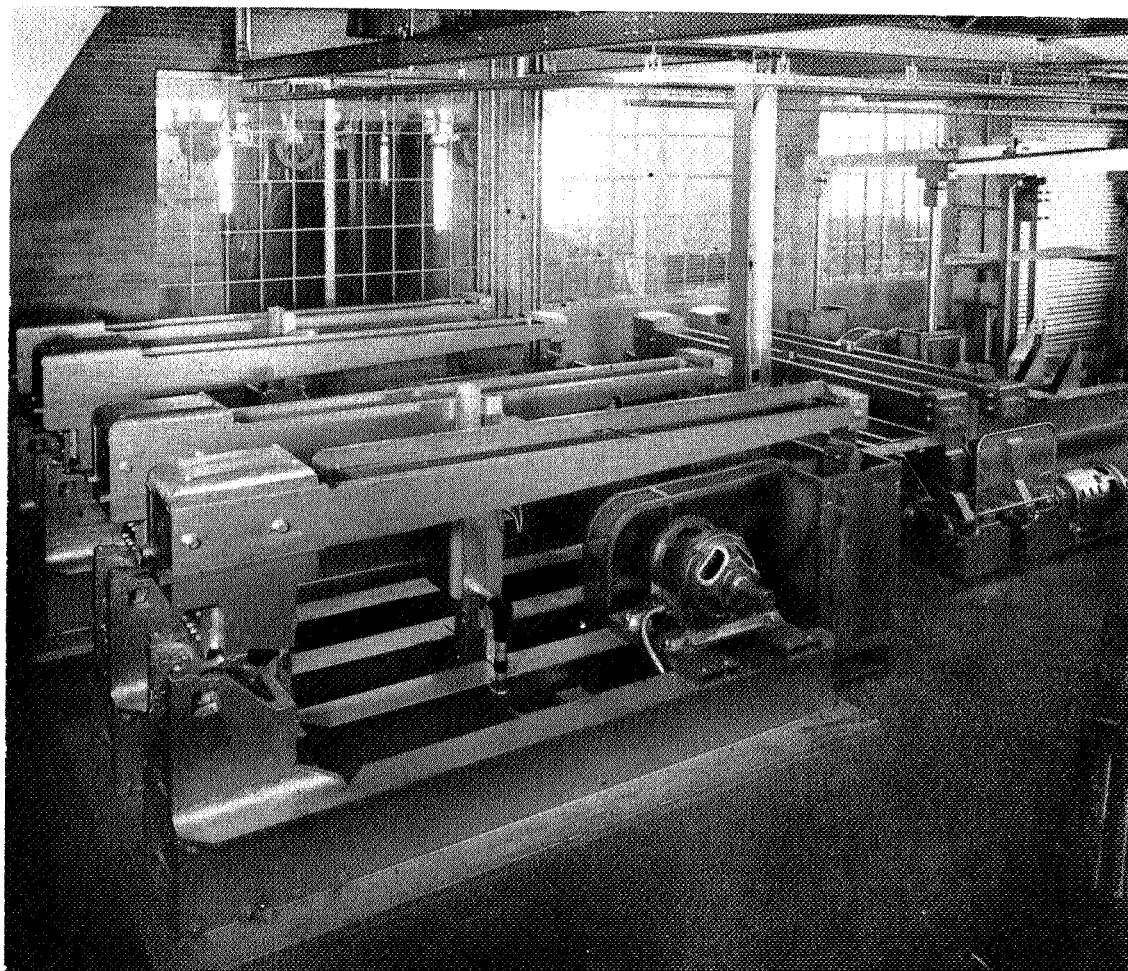


Figure 4.- Direct-stress fatigue machines for testing structural units.

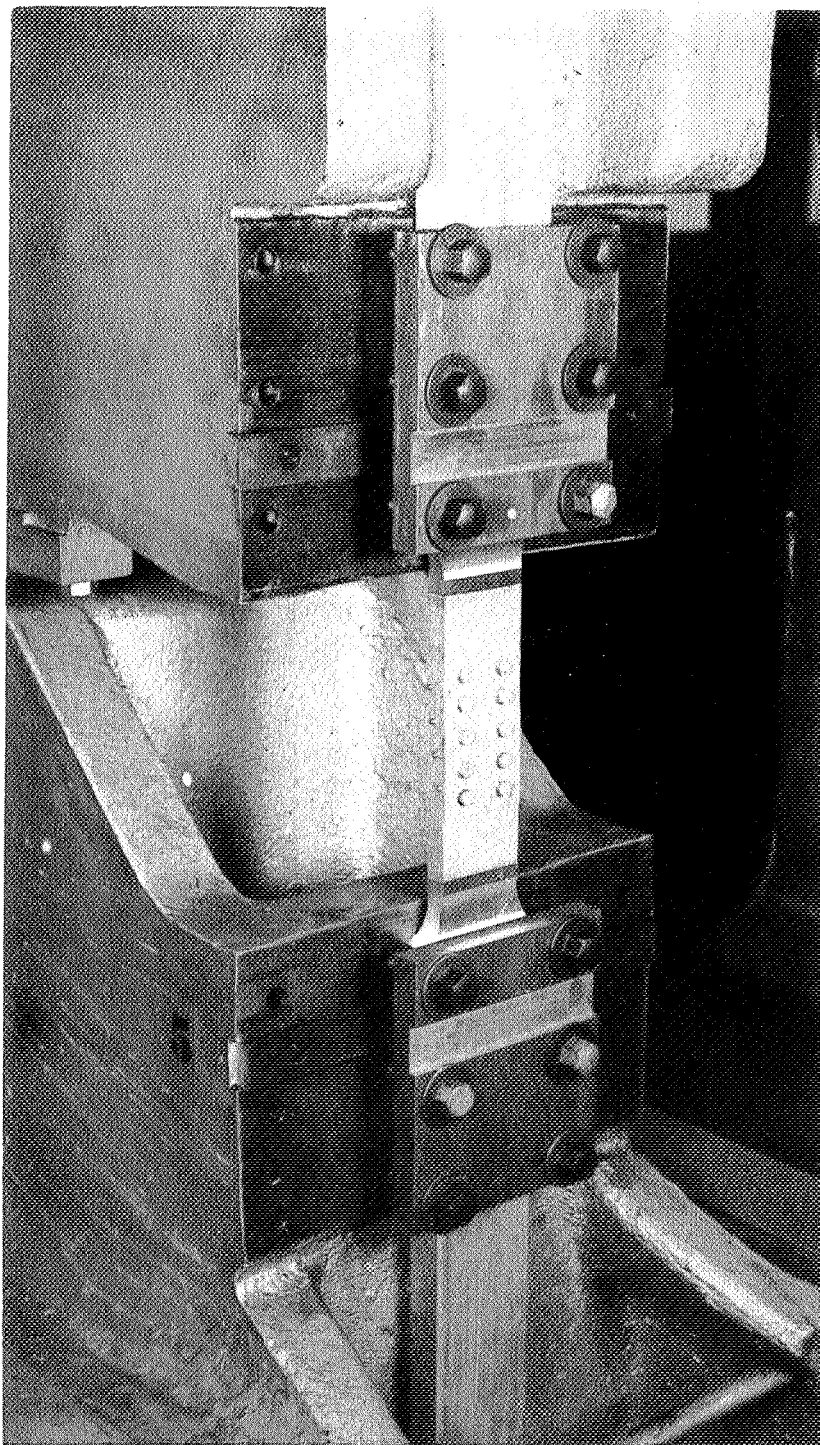
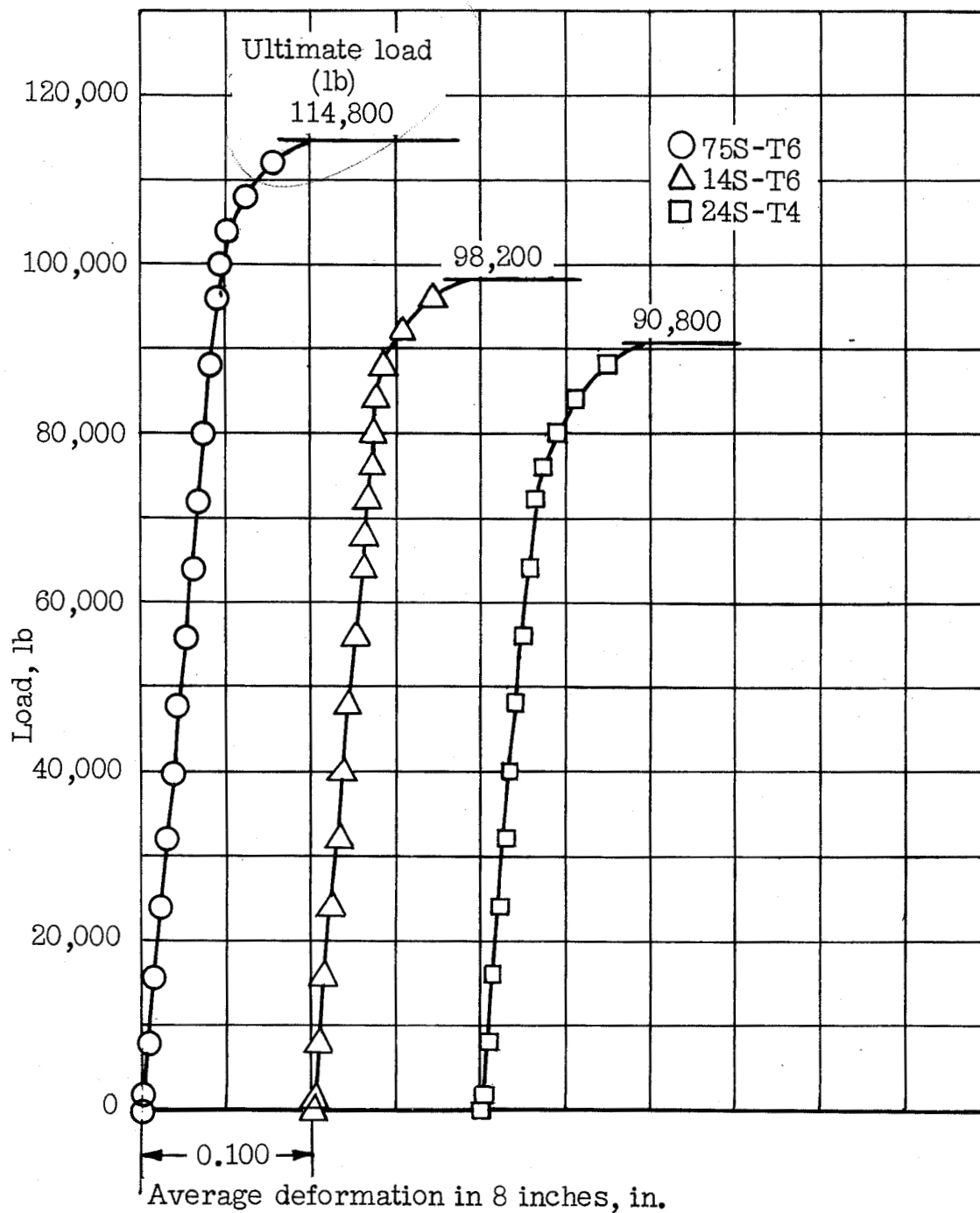
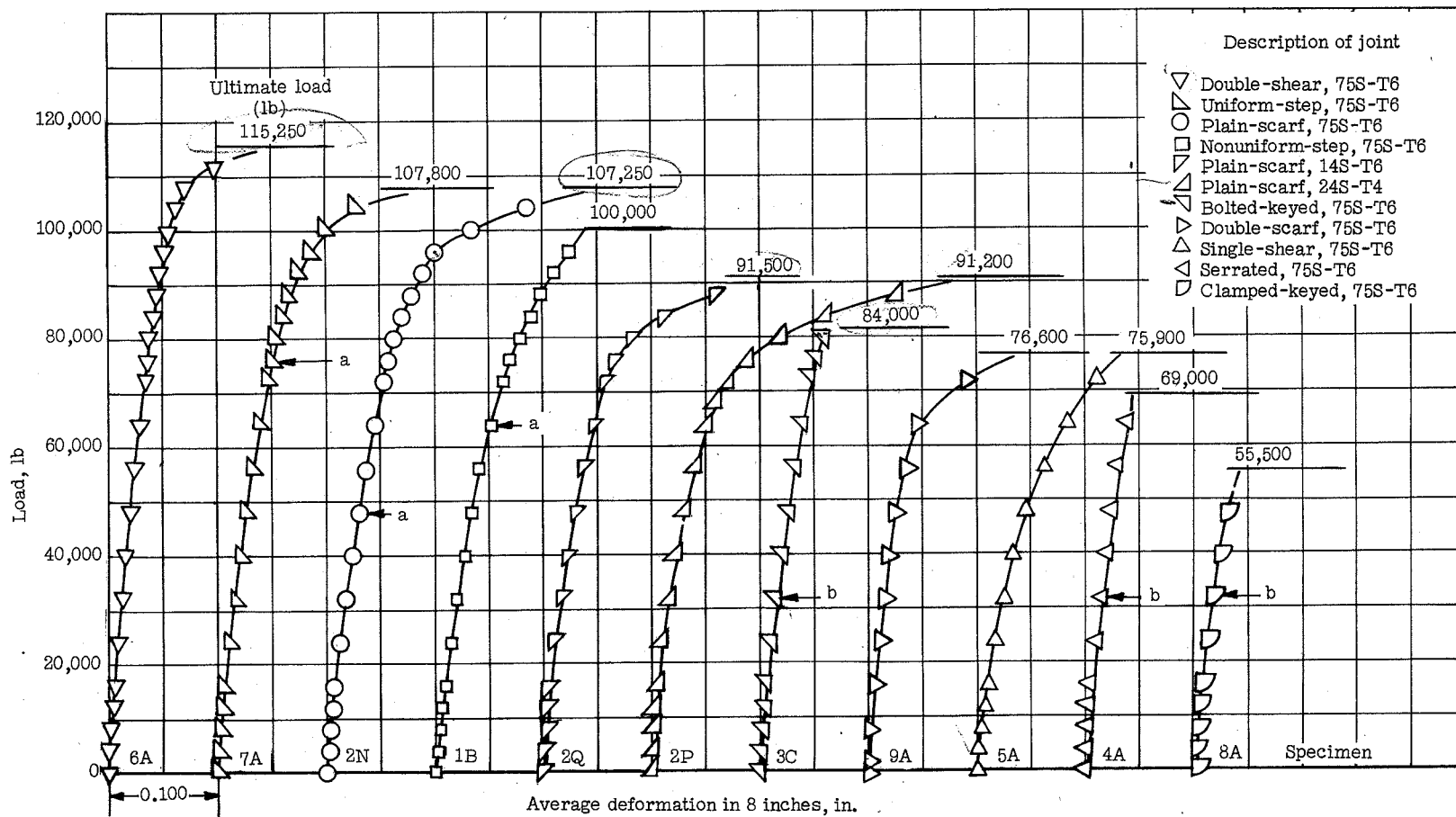


Figure 5.- Setup for direct-stress, tension-compression, fatigue test for high-strength aluminum-alloy bolted joints.



(a) Monobloc specimens. Three alloys.

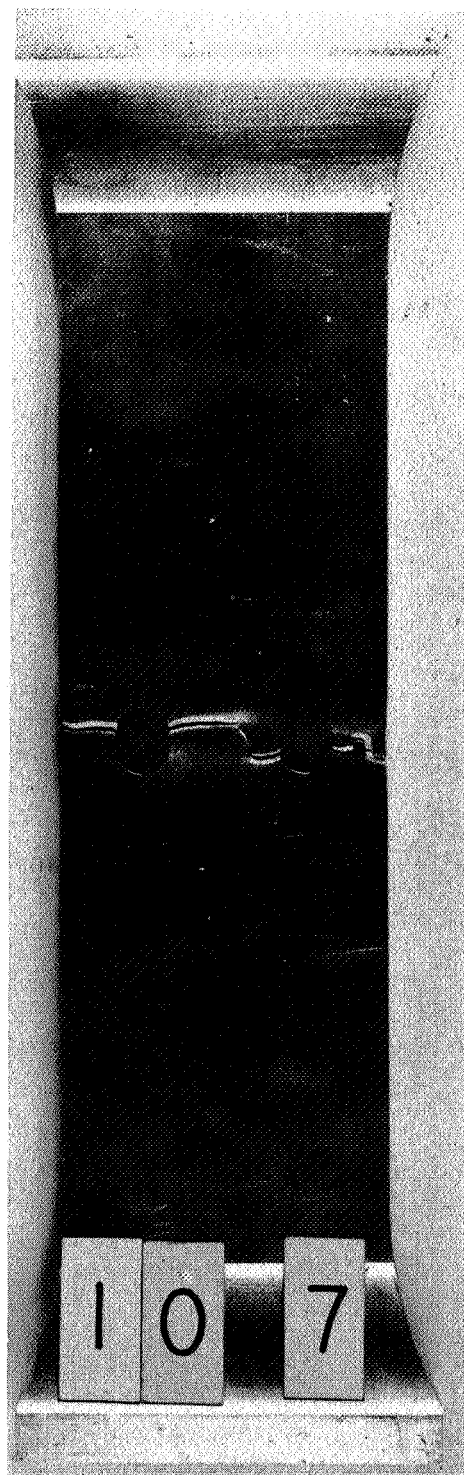
Figure 6.- Static tensile load-deformation curves for high-strength aluminum-alloy specimens.



(b) Joint specimens; three alloys.

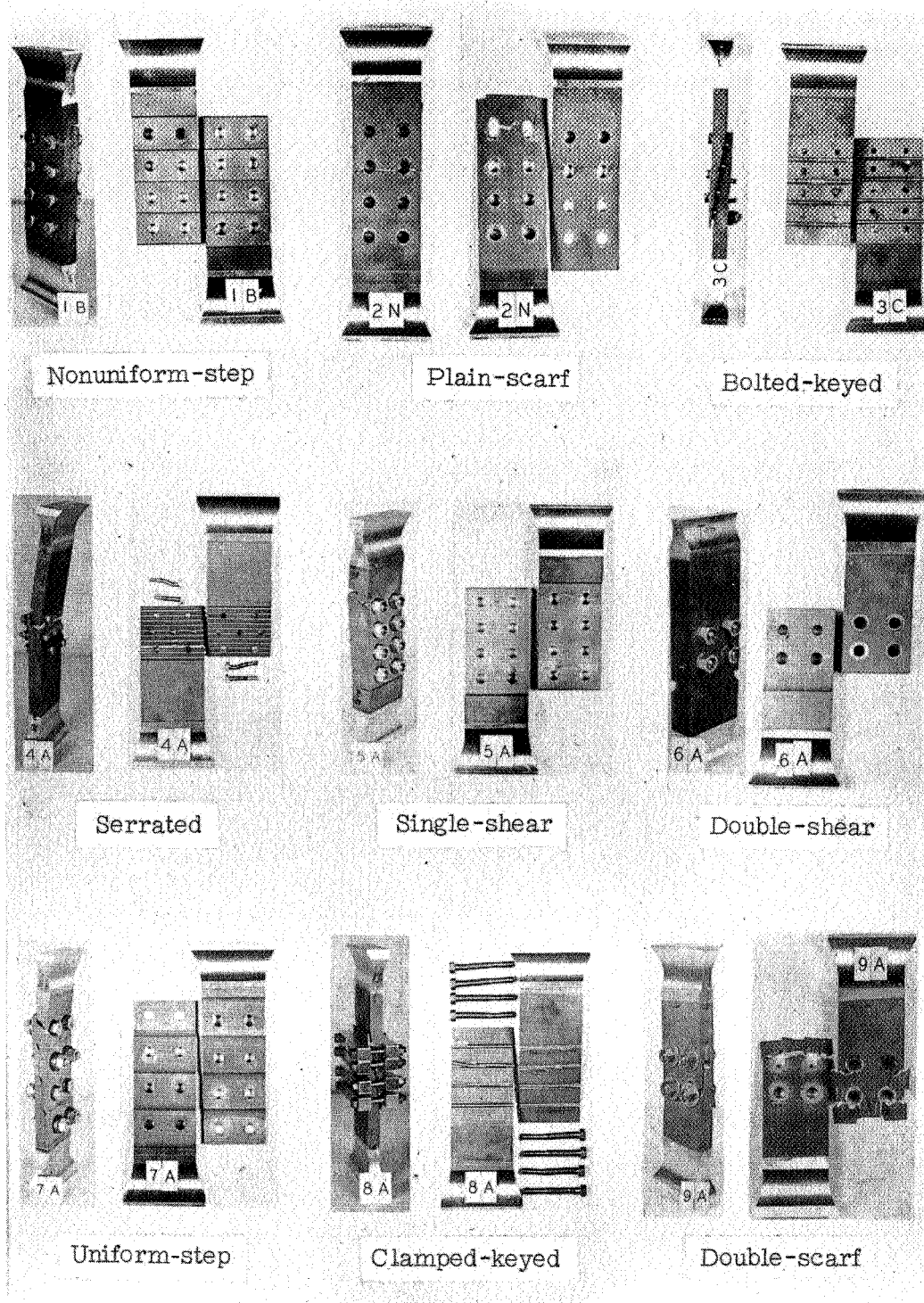
a, noticeable bending; b, noticeable separation of faying surfaces.

Figure 6.- Concluded.



(a) Monobloc specimen.

Figure 7.- Static fractures of 75S-T6 aluminum-alloy specimens.



(b) Joint specimens.

Figure 7.- Concluded.

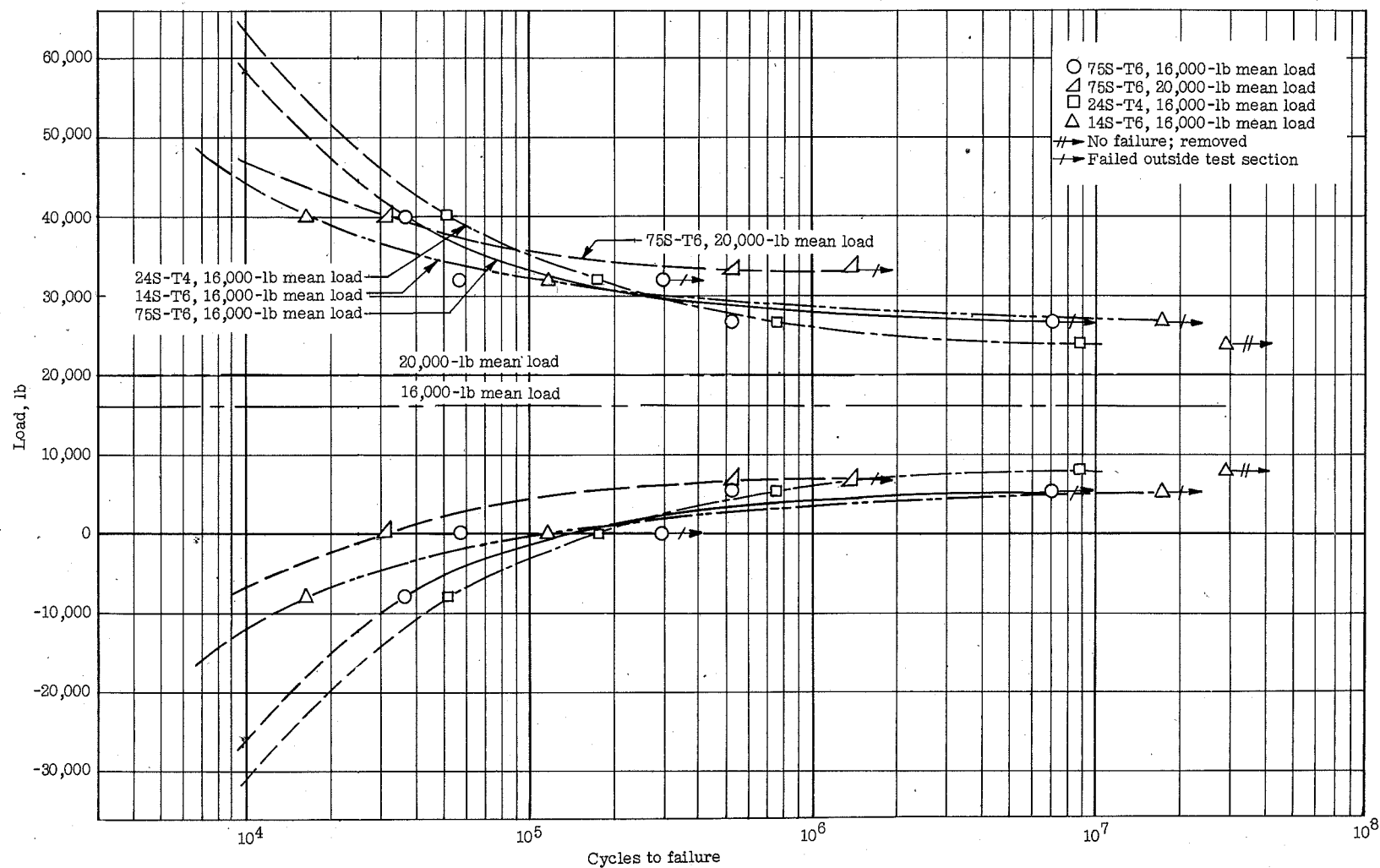


Figure 8.- Direct-stress fatigue curves for high-strength aluminum alloys at 16,000- and 20,000-pound mean load. Monobloc specimens.

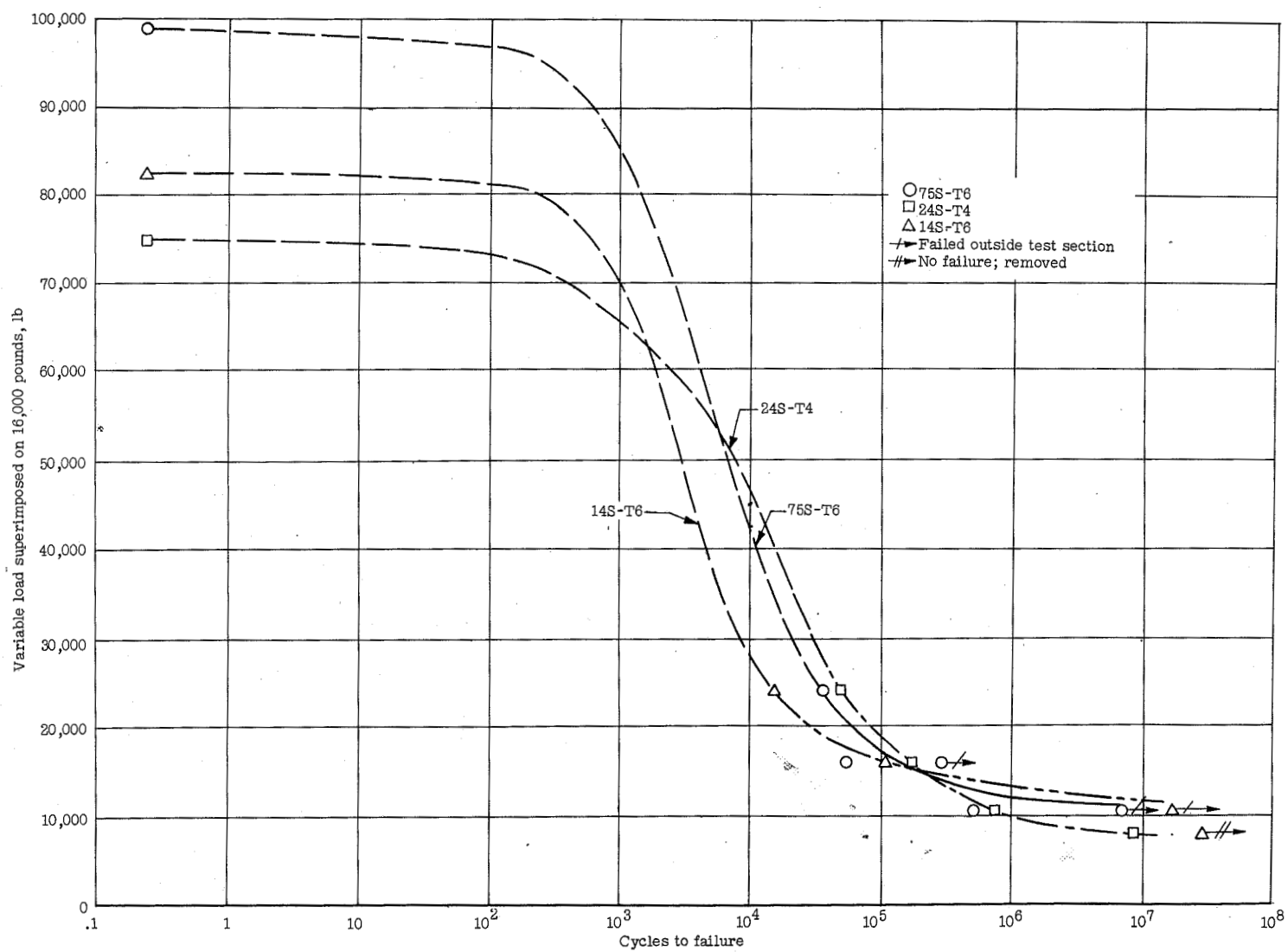
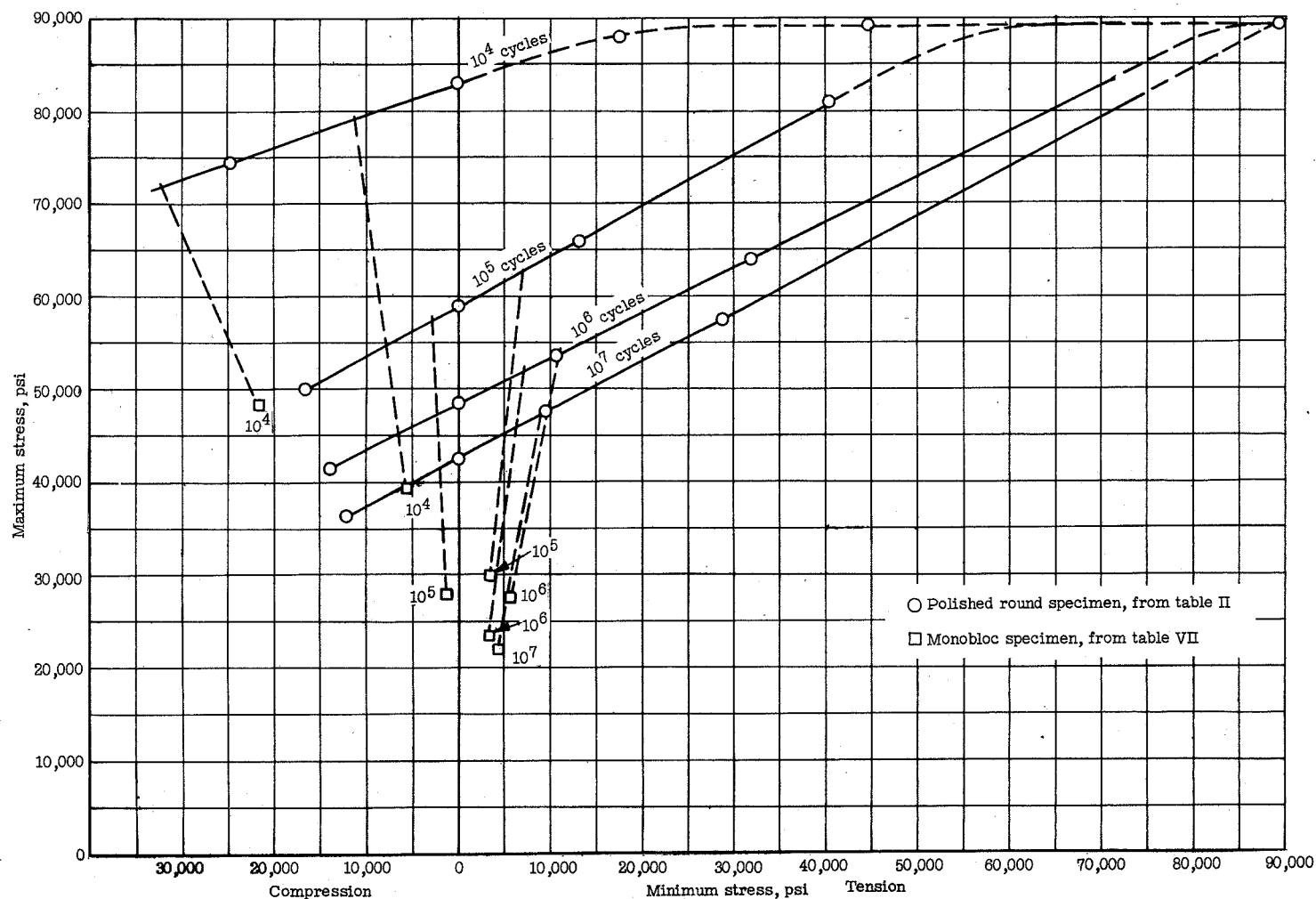
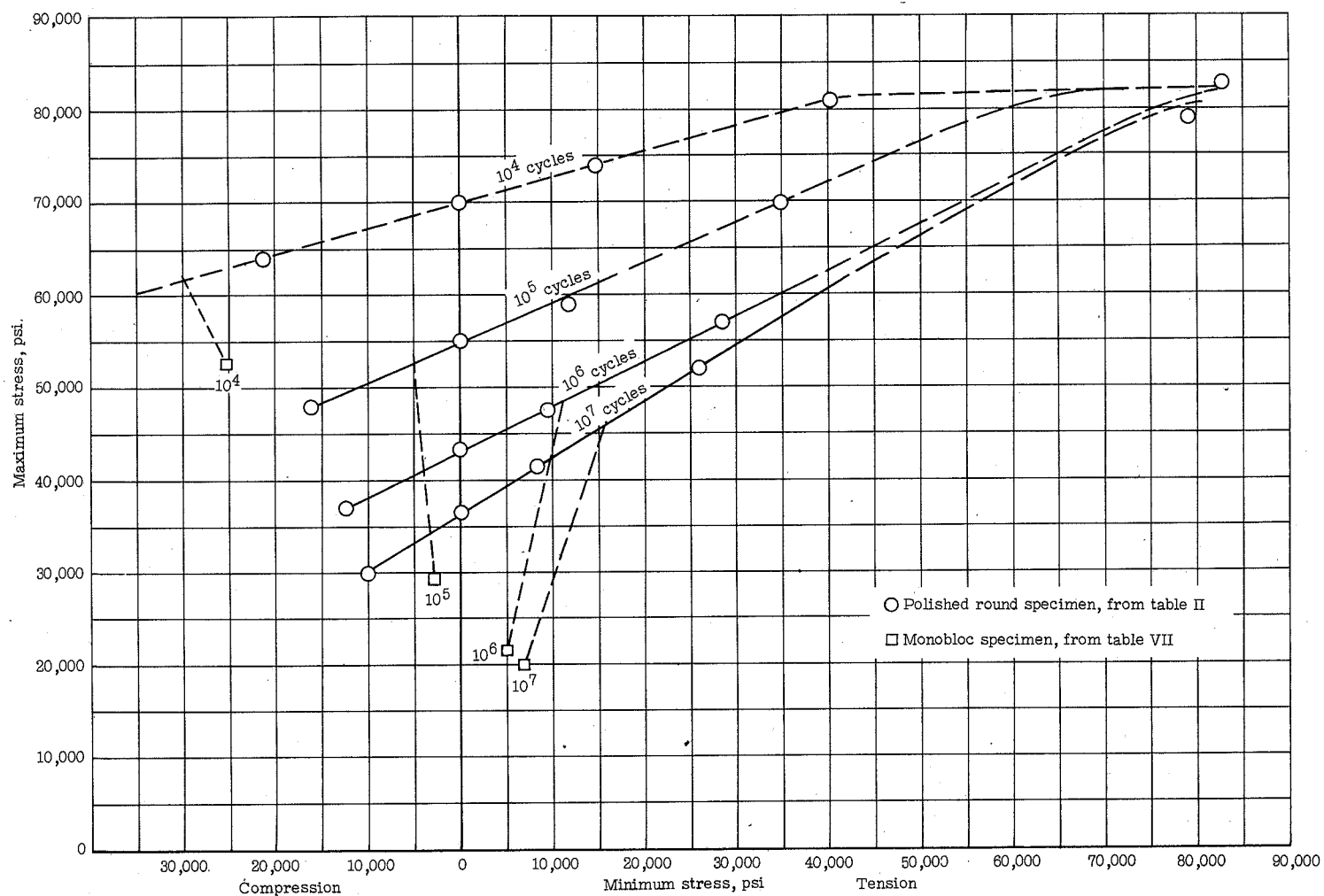


Figure 9.- Direct-stress fatigue curves for high-strength aluminum alloys. Monobloc specimens.



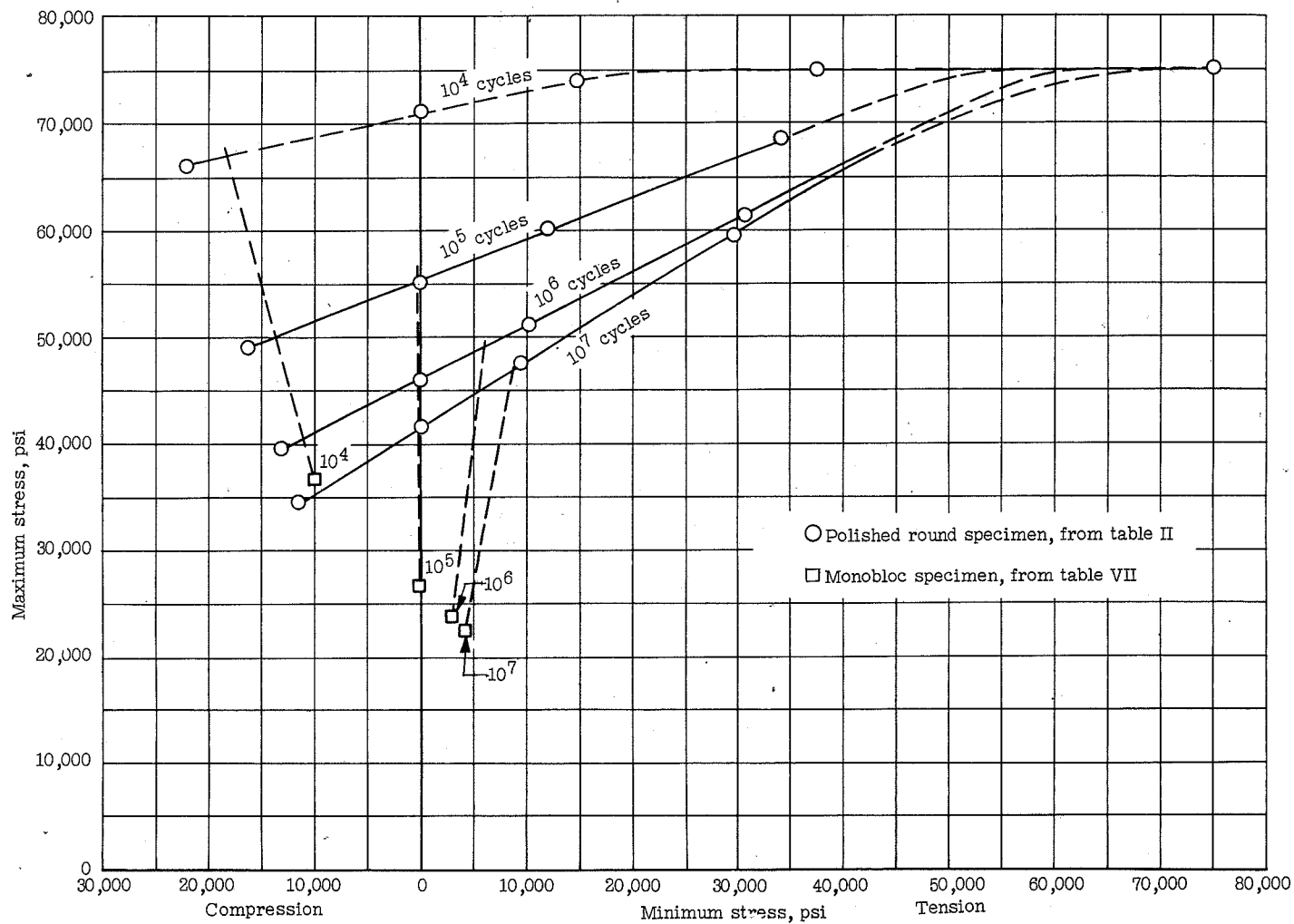
(a) 75S-T6 extruded bar.

Figure 10.- Results of tests on monobloc specimens compared with results for polished round specimens.



(b) 24S-T4 extruded bar.

Figure 10.- Continued.



(c) 14S-T6 extruded bar.

Figure 10.- Concluded.

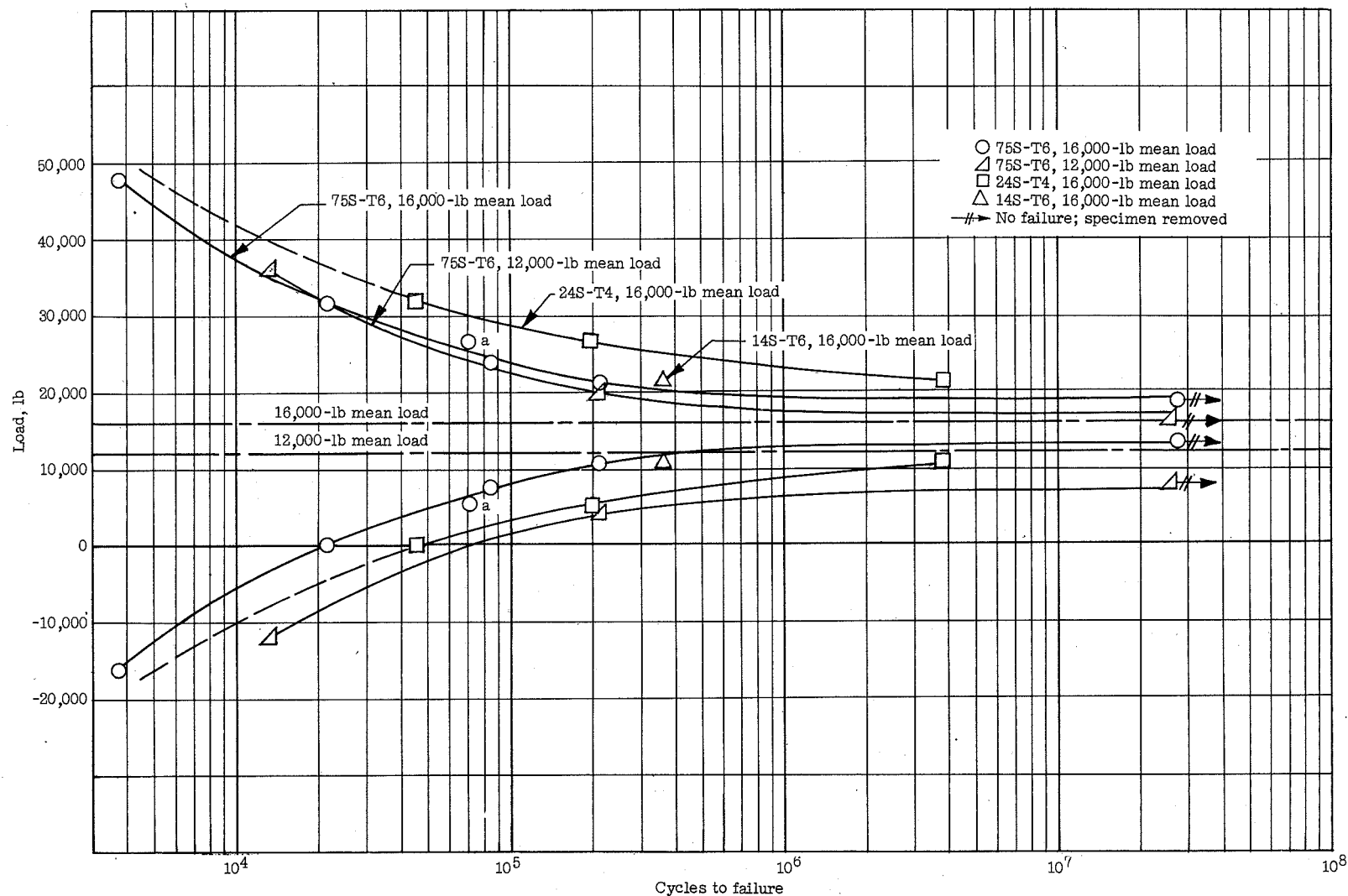


Figure 11.- Direct-stress fatigue curves for high-strength aluminum-alloy bolted joints. Plain-scarf joints. a, two points, one the result of test on specimen treated with Molykote on faying surfaces.

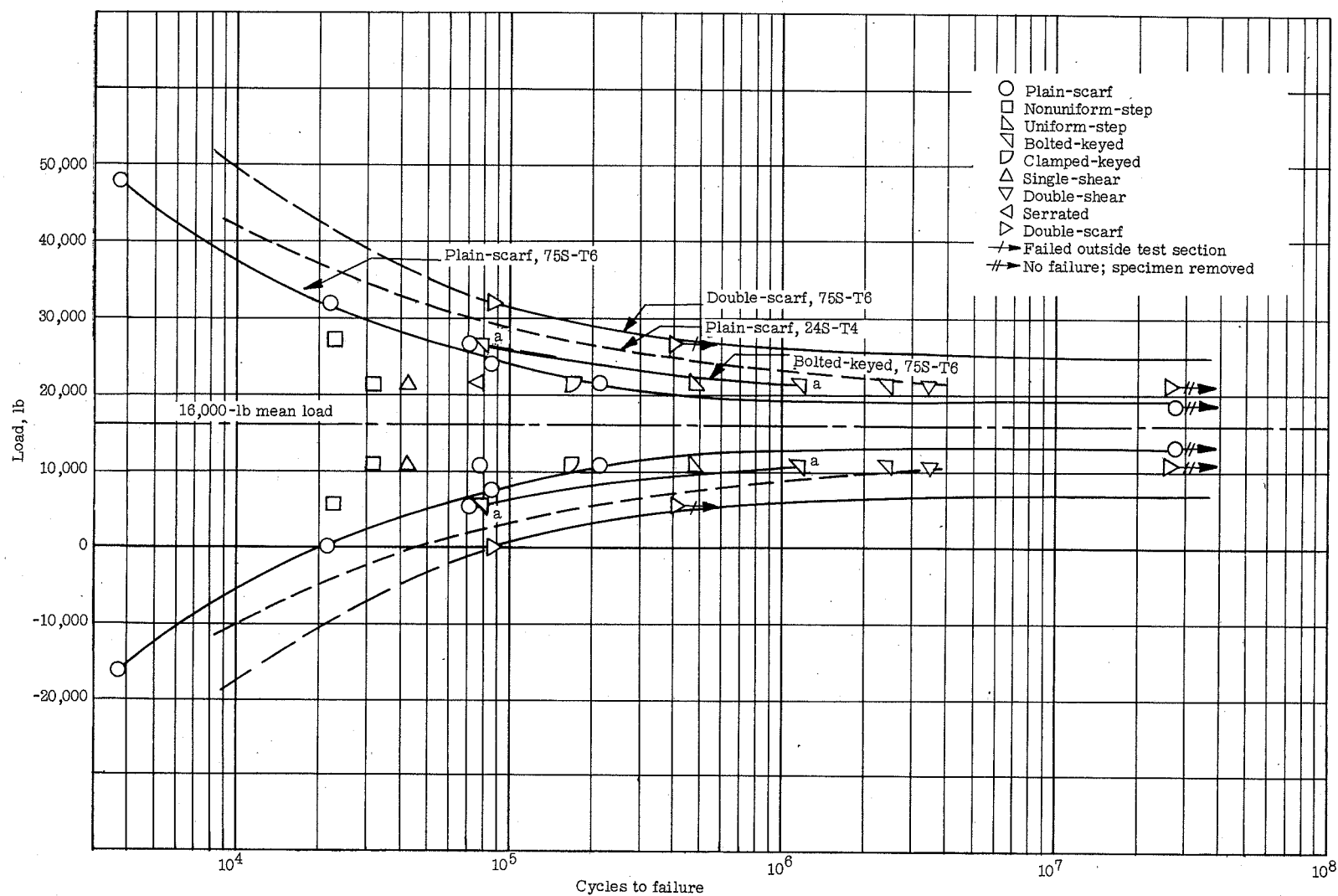


Figure 12.- Direct-stress fatigue curves for high-strength aluminum-alloy bolted joints. 75S-T6 joints. a, keys driven in after assembly.

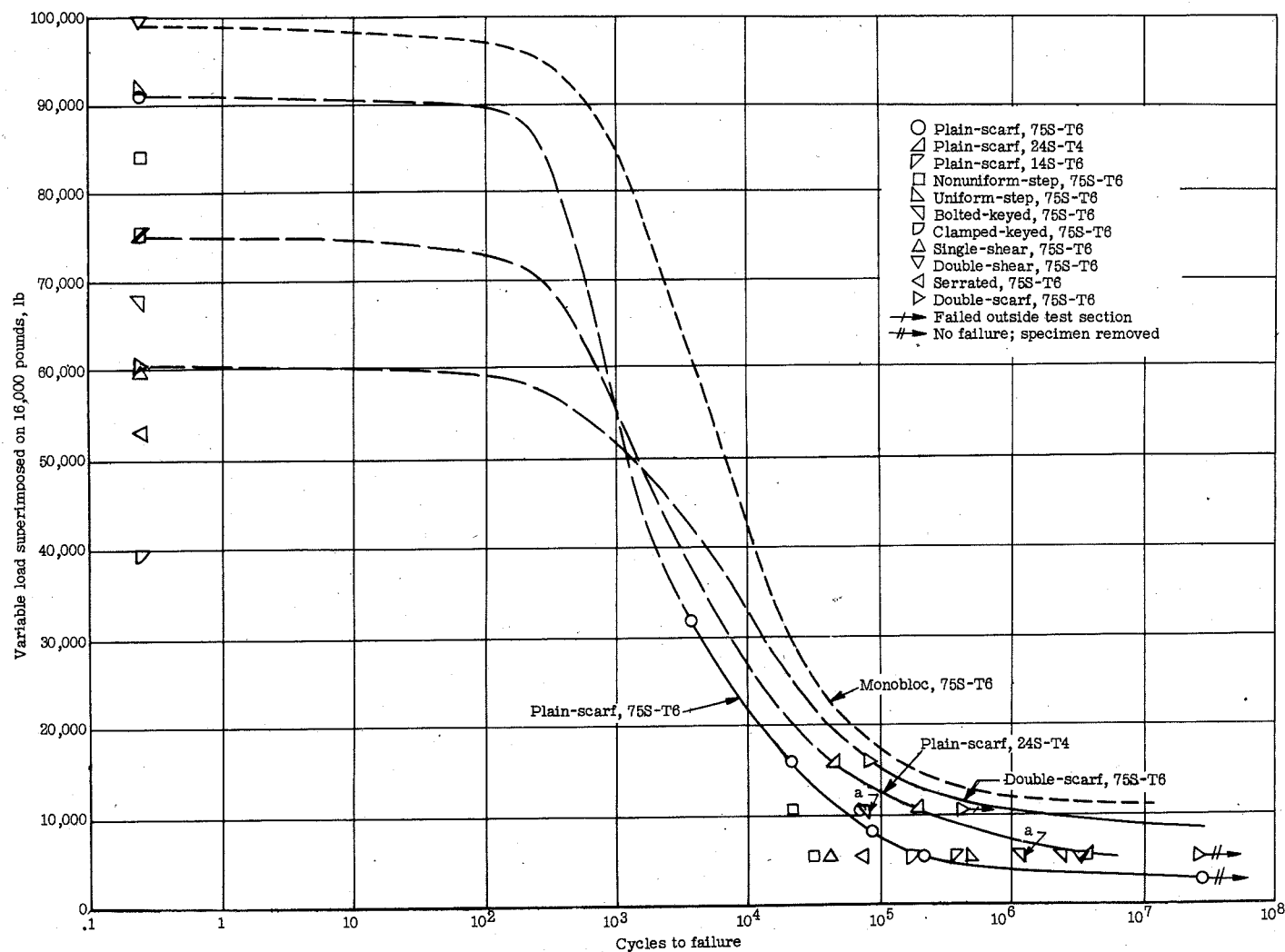


Figure 13.- Direct-stress fatigue curves for various high-strength aluminum-alloy bolted joints. a, keys driven in after assembly.

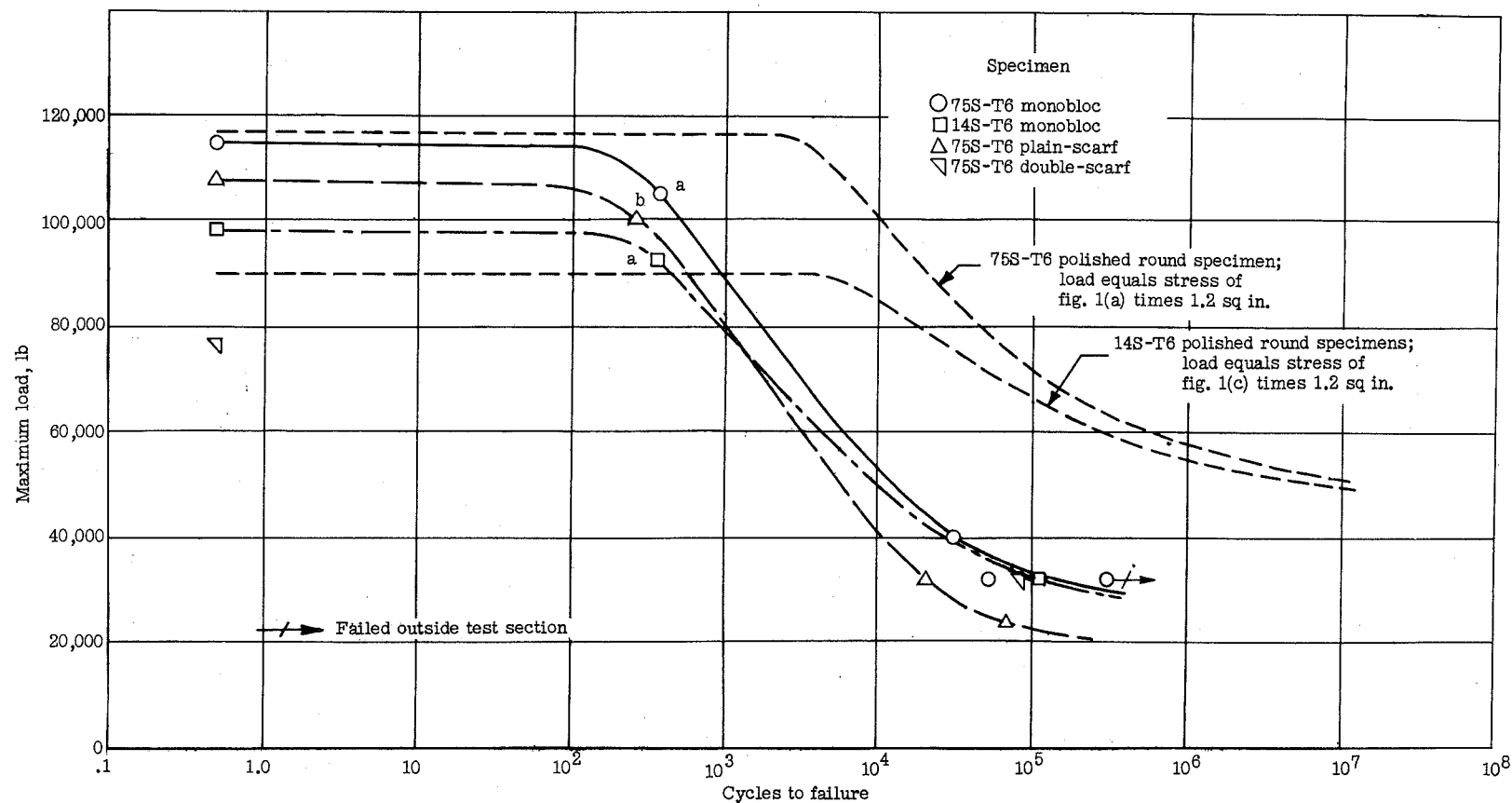
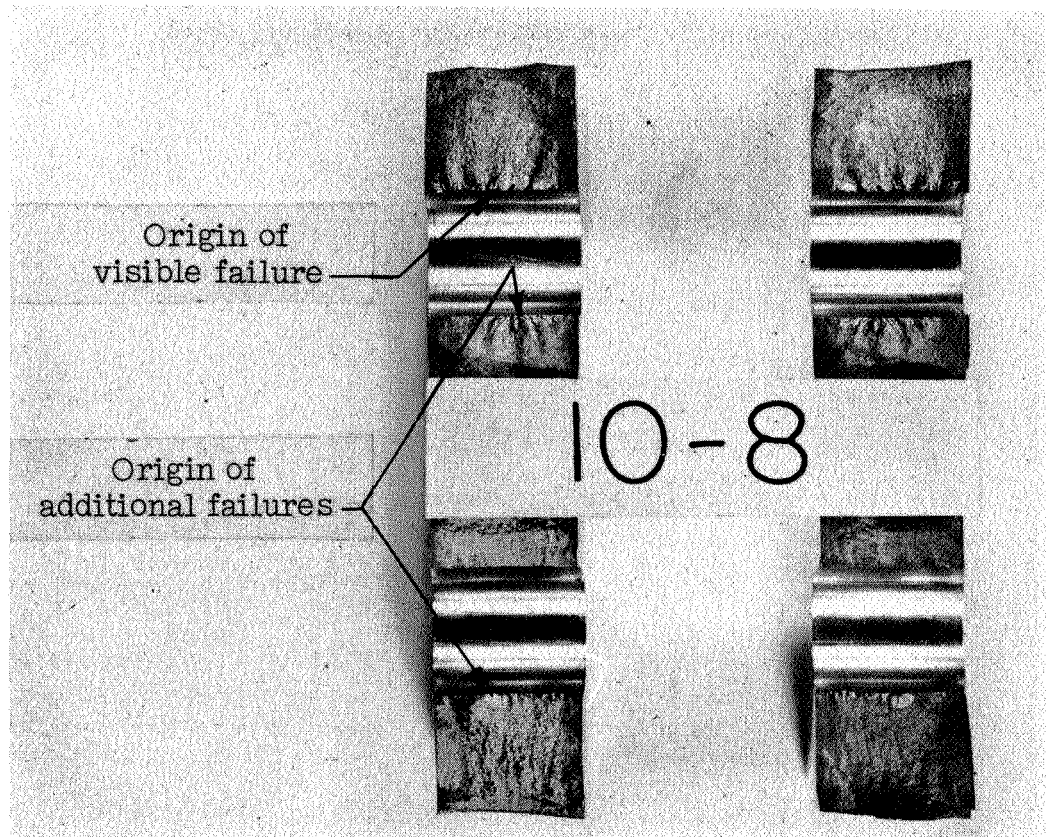
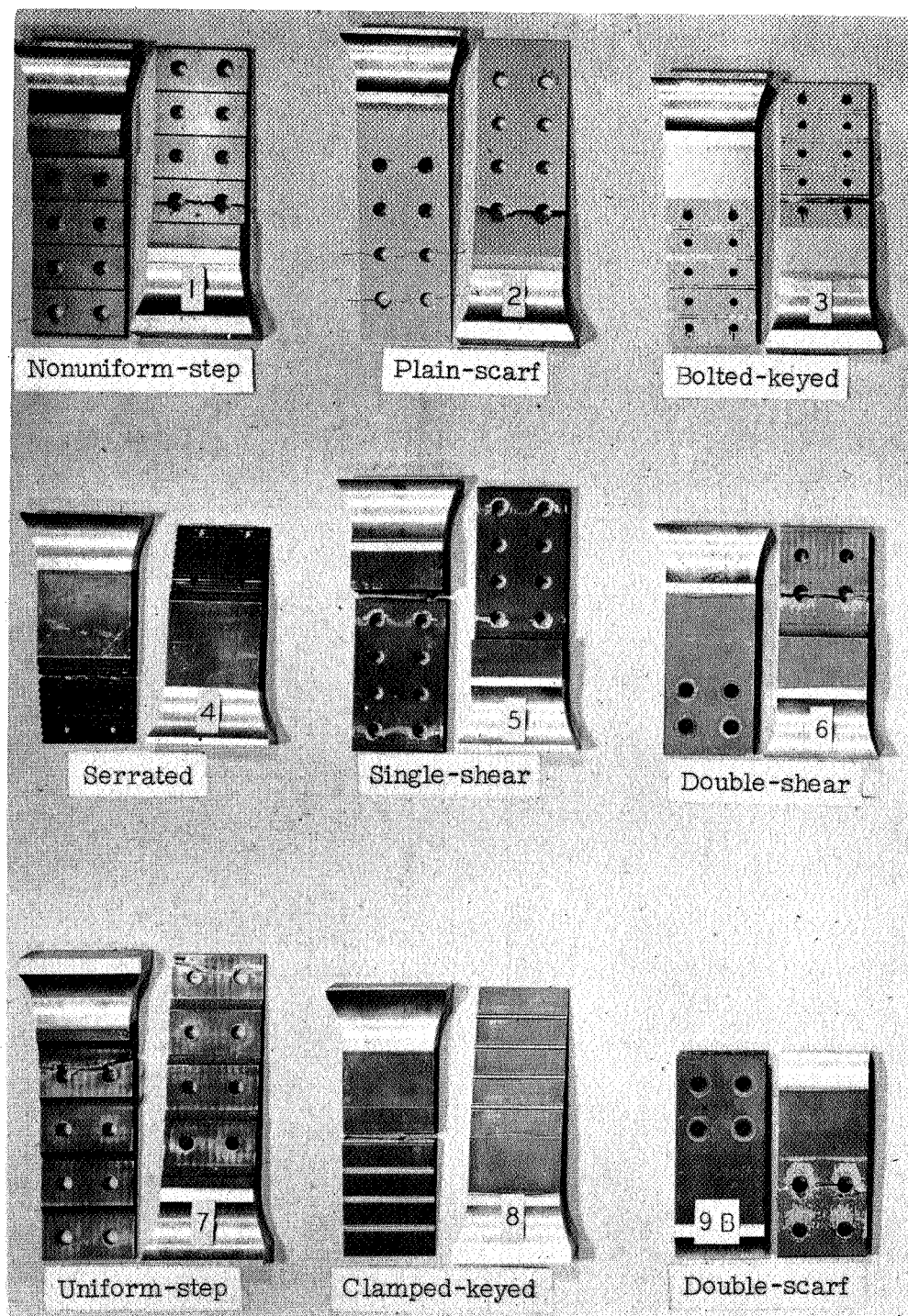


Figure 14.- Direct-stress fatigue curves for various high-strength aluminum-alloy specimens for zero stress ratio. a, cycled in static testing machine; b, cycled in static testing machine after previous test history.



(a) Failure in monobloc specimen.

Figure 15.- Typical fatigue failures.



(b) Fatigue fractures of 75S-T6 aluminum-alloy bolted joints.

Figure 15.- Concluded.